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Self-Consolidating Concrete (Phase I & II)

FINAL REPORT
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16. Abstract

This report summarizes the two-phase research on Self-Consolidating Concrete (SCC) in New Jersey. Phase I involves collecting actual field SCC mixes that were used for casting non-structural concrete components such as tee walls and noise walls. In addition, laboratory mixes were also made to evaluate the mechanical properties and the durability of SCC with various pozzolanic materials. In Phase II, the feasibility of using SCC in drilled shaft construction was evaluated on the new viaduct construction at the intersection of the GSP/I280 near Newark, NJ. SCC was used in the drilled shaft foundations of this project as part of the NJDOT's SCC implementation plan with support from the Innovative Bridge Research and Construction Federal program. Fresh mix tests as well as visual inspection were performed; and specimens were collected to perform laboratory tests. All three shafts were instrumented with temperature sensors and cross-hole sonic logging (CSL) along the shaft length. Results from Phase I and II showed that SCC can be successfully made using viscosity modified admixture (VMA) or solely using super plasticizer (namely the polycarboxilate type) by properly adjusting the paste volume and coarse to fine aggregate ratios. SCC can also be made to equivalently match the mechanical properties and durability of high-performance concrete (HPC) by substituting Portland cement with pozzolans and other cementitious materials. Furthermore, based on the observations of the field mixes, more fundamental knowledge on SCC need to be disseminated to the contractor. It is recommended that the spread test be used in the field for classifying the fresh concrete properties of SCC as a screening test. For more quantitative results, it is recommended that the spread test be used in conjunction with other segregation tests, such as the J-ring test in order to determine the consistency of the mix.

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EXECUTIVE SUMMARY

Self-consolidating concrete (SCC) is a high viscosity concrete that flows freely under its own self-weight without compaction and with minimal segregation. This leads to lower energy cost, lower stress on the formwork, reduced labor cost, and elimination of the potential human error in consolidation of the concrete. The concrete becomes more consistent with equal dispersions of the cementitious paste and aggregates. It was first developed in Japan in 1988 to achieve durable concrete structures by improving quality in the construction process. Since then, it is being rapidly adopted in many European countries and it is already on the market at an affordable price in those countries, however, adoption of SCC technology is still lagging in the United States. A number of factors have attributed to this: the absence of formal guidelines and specifications; the absence of mix design criteria; the absence of established reliable quantitative tests to assess flowability and segregation, and the need for experienced and skilled labor for SCC mixing, placement, and testing. Subsequently, it was found to offer economic, social and environmental benefits over traditional vibrated concrete construction. Since then, interest in its use has spread throughout the world especially for precast concrete applications, and with building construction. As a result, there is an effort to use SCC for bridge construction by the federal highway administration. However, SCC is a relatively new and more complex material, and the properties are not fully understood. Furthermore, with the limited standard specification on mixing, samplings, and testing SCC, guidelines and specification are needed for quality control and assurance of structures made with SCC.

This project focuses on developing recommendations for the New Jersey Department of Transportation (NJDOT) on the use and implementation of SCC. The project was divided into two phases: Phase I was the field assessment of SCC mixes for non-structural Class I precast concrete and Phase II was to assess the ready-mix SCC implemented in the construction of drilled shaft. Phase I also involved laboratory mixes that were used to assess the effect of pozzolans and other cementitious materials on the mechanical properties and durability of SCC.

Phase I was to observe and test the construction of SCC tee-wall and noise wall made by two precast plants, J.R. Slaw, Inc. (Slaw), located in PA, and Fort Miller, Inc. (FM) precast plants located in NY. The approach for the two plants were quite different, where the Slaw mix design utilized an approximately 50/50 coarse to fine aggregates ratio and viscosity modified admixture (VMA) to control the SCC characteristics, whereas the FM mix design used regular (approximately 70/30) coarse to fine aggregate ratio and super plasticizer only. Although the slump flow using the spread test of both mixes were in acceptable limits of the SCC standard specification, both companies applied slight vibration to the precast components to ensure proper finish and consolidation. In addition, because of the high coarse to fine aggregates ratio, the FM mix had more segregation and failed the L-Box and J-Ring tests. Thus, it is recommended that the segregation tests using either the J-Ring or L-Box tests should

be added and performed in conjunction with the spread test to determine the fresh concrete properties of SCC.

In addition to the plant mixes, laboratory SCC mixes were made to determine the effect of pozzolans and other cementitious materials on SCC. Results showed that the mechanical properties and durability of SCC can be enhanced by adding pozzolanic materials and/or slag cement. It is recommended that pozzolanic materials be used in SCC. It is also suggested that the coarse to fine aggregate ratio to be controlled at 50/50 to avoid segregation.

During Phase II of the project field applicability of SCC mixes in drilled shaft applications was thoroughly tested. Three out of five shafts were instrumented with strain and temperature gages to monitor the behavior of SCC during hydration and in curing phases. Fresh concrete testing was also performed to evaluate existing testing procedures and identify those that are reliable and easily implementable under field conditions. Moreover, concrete cylinder specimens were taken to verify the design strength requirements. Finally cross-hole sonic logging tests were performed to test the continuity and integrity of the drilled shaft profile and cross section.

Performance of the SCC obtained from the drilled shafts in Phase II was found to be satisfactory. All mixes including the mix from the demonstration shaft passed the 28-day requirements. The only problem that was encountered was during the pour of the demonstration shaft. Segregation due to high slump flow was observed in the cylinders during testing which adversely affected the strength of this mix. This problem was overcome in the following drilled shaft pours by restricting the slump flow requirement to between 24 and 28 inches. Cross Seismic Logs (CSL) data showed homogenous concrete in the shaft with no defects and field tests showed that the mix was within the spread slump test and J-ring test acceptability criteria. However, SCC in drilled shaft should not be dropped from heights more than 6 feet. For higher drops, a tremie should be used to avoid segregation. Mechanical properties of the SCC obtained from those shafts were observed to be identical.

Test results from the cross-hole sonic logging indicated that there are no air pockets in any of the shafts. This means that the SCC supplied was able to flow through the dense reinforcement layers within the drilled shaft cage. Two out of the five fresh concrete tests were found to be suitable for quality control testing on site. These tests are “C1621/C1621M-06 Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring” and “C1611/C1611M-05 Standard Test Method for Slump Flow of Self-Consolidating Concrete”. These tests are easy to apply in the field and more importantly together they can test the flowability as well as the passing ability of concrete supplied to the site.

INTRODUCTION

SCC can be defined as concrete that does not need compaction or vibration. It is a concrete that has high flowability without segregation. The material is able to flow under its self-weight into corners of formwork and through closely spaced reinforcement without vibration or compaction, leading to a more industrialized production process, reducing labor cost and eliminating potential human error from vibrating the concrete. In consequence, the concrete structure becomes more consistent and reliable. Hence, the use of SCC is spreading rapidly around the world, especially in Japan and Europe. However, the use of SCC in the United States is only limited to precast plants in a few states. Part of the reason is due to the limited knowledge and experience with the new material, lack of quality control and assurance, and no standard specifications for testing SCC. There is more experience with antiwashout underwater concrete, Antiwashout concrete is cast underwater and segregation is strictly inhibited by adding a large amount of a viscous agent made of water-soluble polymer that prevents the cement particles from dispersing into the surrounding water. However, it was found that antiwashout concrete is not applicable to structures in the air for two reasons: First, entrapped air bubbles could not be eliminated due to the high viscosity, and second, compaction in the confined areas around reinforcing bars was difficult. Therefore, SCC was developed and investigated for improved workability and performance.

Fresh concrete can easily attain high flowability by simply increasing the water-to-binder ratio (w/b), however, this will lead to segregation and lower durability. In order to successfully develop SCC for highway structures, mineral and chemical admixtures such as pozzolans, high-range water-reducing agent (HRWRA), and viscosity-modifying admixture (VMA) need to be added to the mix design. Moreover, the absolute volume of coarse aggregates used in the mixture needs to be limited to reduce interparticle friction that prevent SCC from flowing under its own weight without segregation [5,6]. Thus, more volume of cement paste is needed to balance the reduced volume of coarse aggregates, leading to higher material cost and higher shrinkage.

There are different methods to produce SCC and we need to evaluate these methods for its proper use in construction projects in New Jersey. Although, the Rutgers team has identified a number of SCC mixes and has produced them in the Laboratory, there is a need to understand the behavior of each mix under the conditions it is being used. Before SCC can be incorporated in NJDOT projects, mix designs and specifications need to be developed. These items should reflect the state-of-art in design of SCC while incorporating factors specific to New Jersey and the availability of SCC producers and need in various projects. Factors to be considered in developing specifications include: aggregate gradation requirements, maximum volume of coarse aggregates, appropriate filler materials and other admixtures, flow and segregation testing methods, durability, and material handling and placement requirements. The following section describes the various objectives and scope of the project based on the discussion and pre-project meeting held at NJDOT with the presence of NJDOT Research Bureau and Materials Division.

OBJECTIVES

The project consists of two Phases: Phase I – Testing of Field and Laboratory SCC mixes and Phase II – Instrumentation and Field Testing of SCC Drilled Shaft Application.

The main objectives of Phase I of this project are:

1. Identify existing SCC mix designs that have been implemented for both cast-in-place and pre-cast applications in New Jersey and other States in the region including Pennsylvania, Virginia, and New York.
2. Determine the available methods currently used to produce SCC and their effects on the mechanical properties and durability for developing and making SCC mixes, i.e., the use of new generation superplasticizers and gradation only versus the use of a combination of new generation superplasticizer and VMA.
3. Develop and administer a testing program to assure that the mix designs developed meet all the standard specifications of structural concrete and its long-term durability including: strength, air content, drying shrinkage, freeze-thaw, rapid chloride permeability, and scaling as well as curing methods. The testing procedures might vary depending on the type of the SCC mix and its field application as was directed by NJDOT.
4. Coordinate efforts with the local concrete producers to make sure that the selected SCC mixes can be produced in the plant and hauled to construction sites similar to regular concrete.

The main objectives of Phase II of this project are:

1. Construct a 30 ft long dummy shaft to identify potential problems of using SCC in drilled shafts and to evaluate acceptable mix design and testing methods.
2. Based on Task 1, adjust mix design and construction methods, if necessary, to properly use SCC in remaining shafts.
3. Instrument drilled shaft cages with strain and temperature sensors and collect samples for field and libratory tests.
4. Perform field tests on fresh concrete and laboratory tests on hardened specimens.
5. Evaluate the feasibility of SCC for drilled shaft construction.

LITERATURE SEARCH

The research team initiated efforts to find the most relevant literature as the first step in the development process to assemble and review current practice, technical literature, research findings of recently completed and ongoing projects, and procedures from domestic and foreign sources. The literature review conducted revealed that there is no clear definition of SCC in the United States. However, according to preliminary work by ASTM C09.47, SCC should have a fluidity that allows self-consolidation without external energy; remain homogeneous in the form during and after the placement; and that it flows easily through reinforcement. In order to achieve these characteristics, the volume of coarse aggregates need to be reduced and limited, while the paste content needs to be increased, and the paste viscosity should be increased to reduce the risk of segregation.

The following section is a summary of the literature review of SCC mixes designs and testing methods currently being used in Japan and Europe and by researchers in the field:

Mix Design

There is a large body of literature related to SCC mix design methods and the development of SCC mixes incorporating various VMA and HRWRA [6, 9–20]. Because the increase in the volume of paste content and the associate cost, most of the mix designs incorporate industrial byproducts such as limestone filler to reduce the amount of Portland cement in the mix design of SCC. There have also been studies addressing durability issues in SCC or comparing the mechanical properties of SCC to normal concrete [8, 14, 21, 22]. However, these studies are still limited and do not address all of the durability issues for highway structures. Moreover, most of these mix designs are based on Japanese and European experiences. SCC mix designs using raw material in United States has not been used.

Testing Methods

As mentioned in the definition, SCC does not require compaction. Therefore, the rheological characteristics of SCC are very important since its consolidation depends on its rheological performance. In ordinary concrete, adequate slump in conjunction with good consolidation practice will yield a dense concrete structure with few air voids. The external forces due to vibration compensate for the variations in plastic concrete and therefore the rheology of concrete could be ignored. Hence only the slump test is performed for testing fresh ordinary concrete. Whereas in SCC, the rheological characteristic cannot be ignored since the concrete need to meet the certain rheological requirements. The plastic concrete is generally described as Bingham fluid where the concrete behavior is characterized by its shear yield stress and plastic viscosity. For SCC, the shear yield stress has to be lower than ordinary concrete in order for the concrete to self-compact.

The rheology of concrete could be measured using a concrete rheometer. A concrete rheometer measures the shear yield stress and viscosity of concrete. The problem with this is that the device is very expensive and the test is impractical to perform at a job site, hence other practical fresh concrete testing methods similar to the slump test of ordinary concrete were developed. These tests include 1) Spread Test, 2) L-Shaped or U-Shaped Box, 3) V-Funnel 4) J-ring, and 5) Sieve Stability. Figure 1 through Figure 4 show tests 1 thru 4. However, it must be noted that these new developed tests do not measure the rheology of concrete directly but they are used to simulate actual environment. Furthermore, there are not enough data to correlate these tests with the rheology of concrete and more so for mix designs that use raw material available in United State. However, for this project, only the spread test, J-ring test, and the L-Box test will be performed to validate the standards that will reflect mix designs using New Jersey raw material.

Spread Test

There are several methods developed for testing the fresh concrete properties of SCC (*15-17*). The most widely used in the US is the spread test. The spread test is similar to the regular slump test using the Abram's cone. The difference between the two methods is rather than measuring the height of the concrete to the height of the cone, the distance of the spread concrete, which is referred as slump flow, is measured. This distance is measured by taking the average of two perpendicular diameters of the spread concrete (Figure 1). The spread of concrete will give a good indication whether the concrete will self-consolidate or not. This measurement varies between a minimum of 24 in. and a maximum of 26 inches for the concrete to achieve good self-consolidation. In addition, the edge of the spread concrete needs to be observed for segregation. In some cases, the time it takes the concrete to spread 20 in. is also recorded as an indication of the viscosity of concrete. This time should be less than 7 second for civil structures.

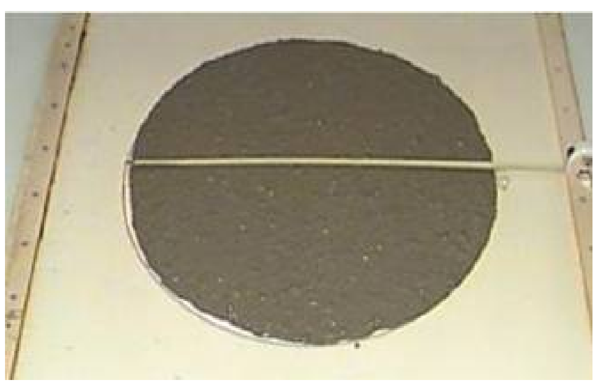


Figure 1. Spread Test (taken from ASTM International 2002)

L-Shaped and U-Shaped Box Tests

Figure 2 shows the L-Box and U-Box tests that are used for measuring the filling as well as the passing ability of SCC under its self-weight. The height H between initial and final concrete level in the U-Box as well as the ratio of H2/H1 in the L-Shape Box need to be measured. In addition to measuring these values, the segregation resistance can be observed by looking at a plateau in front of the reinforcement layer. If there is a plateau, then the concrete is either blocked or segregated.

V-Funnel Test

Figure 3 shows the V-Funnel which is used to test the viscosity of concrete by measuring the time it takes for the concrete to completely flow through the orifice. It is a good indicator for adjusting the HRWRA dosage or amount of VMA powder.

J-ring Test

Figure 4 shows the J-ring test which is similar to the L-Box and U-Box test but instead of using a box, a ring of reinforcement is used. The method of testing is similar to the spread test but with the J-ring being the obstacle. Besides the diameter of the spread of concrete, the height from the center of the J-ring to the concrete have to be recorded. This spread measurement in this test is compared with that from the spread test without the J-ring as an obstacle to provide an indication of the passability of concrete through rebars.

Sieve Stability Test

This method checks the stability (resistance to segregation and bleeding) of concrete. A sample of concrete is poured over a 5-mm sieve and the amount of mortar passing through the sieve in a two-minute period is measured.

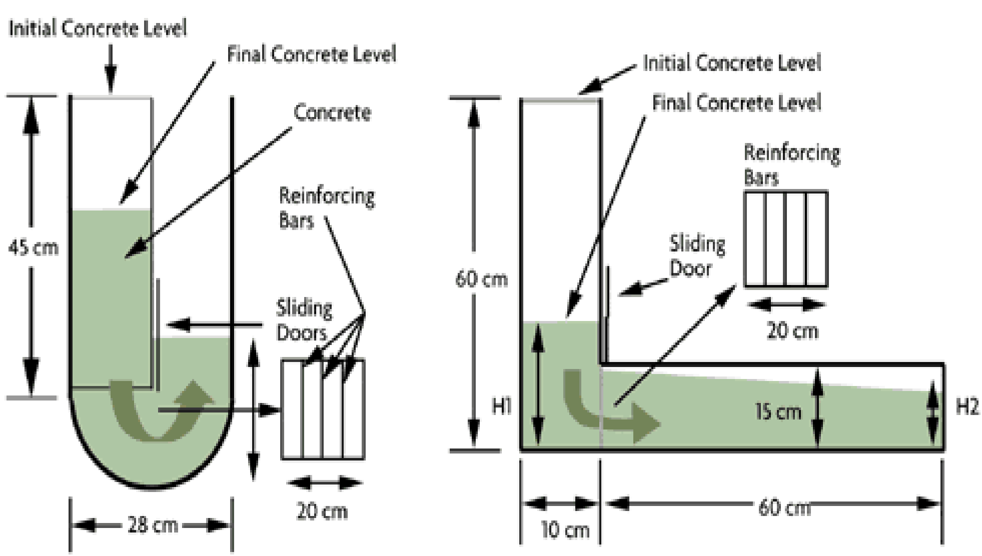


Figure 2. U-Shaped Box and L-Shaped Box (taken from ASTM International)

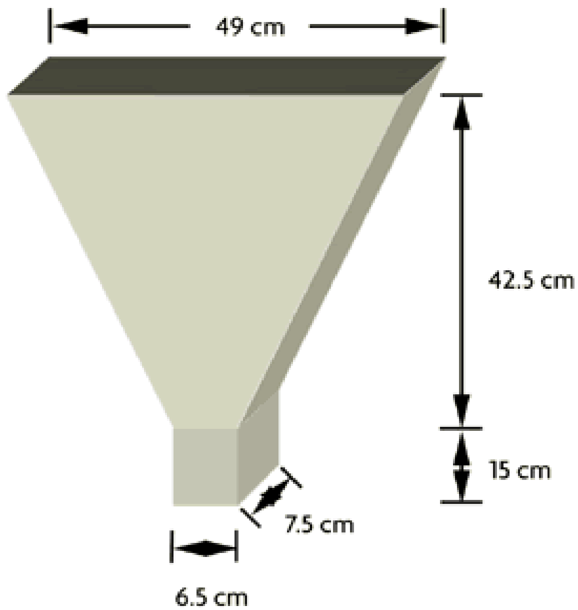


Figure 3. V-Funnel (taken from ASTM International)

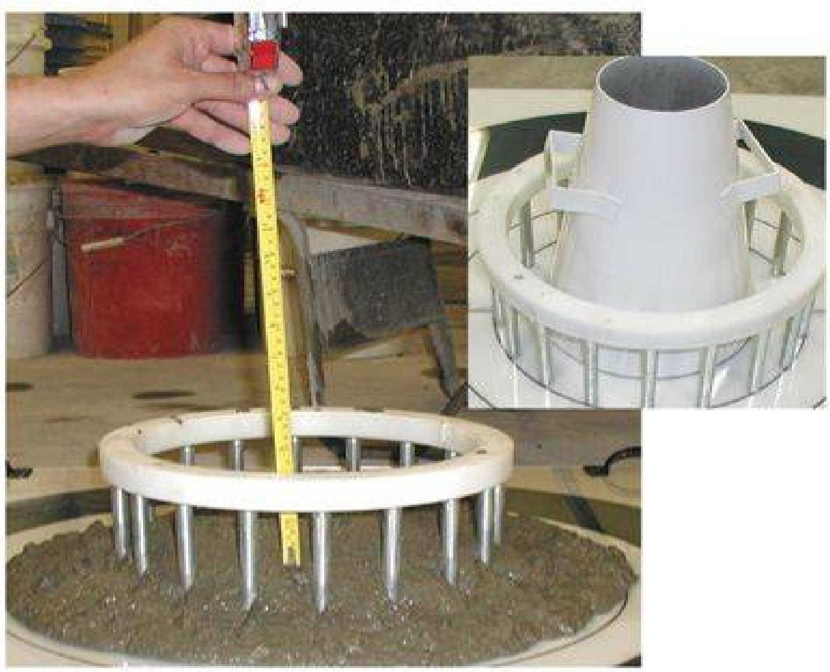


Figure 4. J-Ring (taken from ASTM International)

PHASE I – TESTING OF FIELD AND LABORATORY SCC MIXES

Field SCC Mixes

A total of three NJDOT SCC mixes were sampled and tested for compressive strength, modulus of elasticity, tensile splitting strength, drying shrinkage, and rapid chloride permeability tests. One of the SCC mixes was sampled at the J.R. Slaw, Inc. (Slaw) precast plant in Pennsylvania. The other two SCC mixes were sampled at the Fort Miller, Inc. (FM) precast plant in New York. The two companies used different approaches on developing the SCC mixes. The Slaw mix was based on a more conventional approach using a combination of VMA and superplasticizer as well as lowering the coarse to fine aggregates ratio such that approximately equal amount of stone and sand were used in the mix design to attain SCC characteristic. The Slaw mix also contained a 20 percent Portland cement replacement by weight of slag cement. FM mixes were similar to a regular concrete mix design with high coarse to fine aggregates ratio but with high amount of superplasticizer to attain SCC characteristic. One of the FM mixes contained 30 percent Portland cement replacement by weight of Class F fly ash. Table 1 summarizes the mix proportions of the field SCC mixes.

Table 1 - Mix Proportions of Field SCC Mixes

Raw Material	**Mixtures Identification**		
(lb/yd^3)	**Slaw**	**FM1**	**FM2**
PC	564	801	524
SF	--	--	--
F	--	--	224
SL	143	--	--
Total Cement. Material	707	801	748
CA	1450 (52%)	1783 (63%)	1729 (60%)
FA	1350 (48%)	1033 (37%)	1136 (40%)
Water	250	288	262
w/CM	0.35	0.36	0.35
SP (oz)	55.9	105	45
AEA (oz)	8.0	12.4	10.3
VMA (oz)	14.0	--	--
Slump (in)	25	24	24
Air (%)	6.0	5.00	5.75

Laboratory Testing Results of Slaw Mix

Table 2 and Table 3 summarize the compressive strength and tensile splitting strength of the Slaw mix, respectively. The Slaw mix has very high compressive and tensile splitting strength of 8,700 psi and 771 psi at 28-day, respectively. Table 4 summarizes the rapid chloride results. Overall, the mix had moderate to high chloride ion penetrability with the lowest average charge passed of 3292 Coulombs. This value is higher than the NJDOT specification for HPC with the maximum permissible charge passed of 2000 Coulombs. The modulus of elasticity and Poisson ratio were also recorded and tabulated in Table 5 and Table 6. As observed in Table 7, the Slaw mix also has very high free drying shrinkage values with a 7-day drying shrinkage value of 0.044%. The 90-day drying shrinkage is also high with a value of 0.079%. It is expected that this mix could lead to a potential cracking problem if the structural components are restrained. Results related to strength and durability are obtained from tests performed at the Rutgers Concrete Testing Laboratory.

Table 2 - Compressive Strength (psi) (ASTM C39) for SLAW (4/1/04) SCC Mix

Day	Specimen 1	Specimen 2	Specimen 3	Average
1	4576	4775	4814	**4722**
3	5889	6525	6525	**6313**
7	6366	7401	7182	**6983**
14	8833	9390	8117	**8780**
28	8754	8196	9151	**8700**
56	9470	8515	9032	**9006**
90	8515	9470	8913	**8966**

Table 3 - Tensile Splitting Strength (psi) (ASTM C496) for SLAW (4/1/04) SCC Mix

Day	Specimen 1	Specimen 2	Specimen 3	Average
1	581	511	527	**540**
3	623	623	471	**572**
7	643	577	621	**613**
14	657	627	617	**633**
28	756	782	776	**771**
56	756	786	796	**779**
90	N/A	786	796	**791**

Table 4 - Rapid Chloride Permeability (Coulombs) (ASTM C1202) for SLAW (4/1/04) SCC Mix

Date	Day	Specimen 1	Specimen 2	Specimen 3	Average
04/29/04	28	4228	4096	4677	**4334**
05/27/04	56	4417	3686	3627	**3910**
06/30/04	90	3388	3162	3327	**3292**

Table 5 - Elastic Modulus (ksi) (ASTM C469) for SLAW (4/1/04) SCC Mix

Day	Specimen 1	Specimen 2	Specimen 3	Average
1	2550	2724	2699	**2658**
3	3287	3244	3287	**3273**
7	3004	3081	3004	**3029**
14	3681	3864	3828	**3791**
28	4541	4574	4487	**4534**
56	4638	4406	4447	**4497**
90	4161	4457	4209	**4276**

Table 6 - Poisson's Ratio for SLAW (4/1/04) SCC Mix

Day	Specimen 1	Specimen 2	Specimen 3	Average
1	0.25	0.23	0.23	**0.24**
3	0.22	0.20	0.20	**0.21**
7	0.21	0.21	0.20	**0.21**
14	0.18	0.17	0.17	**0.17**
28	0.25	0.23	0.25	**0.24**
56	0.29	0.25	0.25	**0.27**
90	0.27	0.26	0.25	**0.26**

Table 7 - Average Length Change (ASTM C157) for SLAW (4/1/04) SCC Mix

Day	Specimen 1	Specimen 2	Specimen 3	Average
1	0.0000	0.0000	0.0000	**0.0000**
3	-0.0200	-0.0190	-0.0490	**-0.0293**
7	-0.0430	-0.0440	-0.0460	**-0.0443**
14	-0.0490	-0.0520	-0.0570	**-0.0527**
28	-0.0650	-0.0620	-0.0700	**-0.0657**
56	-0.0770	-0.0730	-0.0780	**-0.0760**
90	-0.0760	-0.0780	-0.0840	**-0.0793**

Laboratory Testing Results of Fort Miller Mixes

Two SCC mixes were acquired from Fort Miller in New York State who was making concrete noise and tee wall for NJDOT. These mixes were designed to be SCC mixes to be used in lightly reinforced barriers and retaining walls. Concrete samples were taken at the batching facility to test and compare the mechanical properties of these mixes. Slump flow tests were also utilized to compare to flowability of the mixes.

Slump flow for all the mixes was below 20 inches and it was observed that vibration was required to consolidate the concrete. Table 8 through Table 12 summarize the results for the mechanical properties of the three FM mixes. As shown in Table 8, although both FM mixes had different mix proportions, they had very similar compressive strength, with the average values of three 28-day cylinders varying between 6100 to 6800 psi. The tensile splitting (as shown in Table 9) and modulus of elasticity (as shown in Table 10) were also similar for both mixes. Even the drying shrinkage of the two mixes was similar with the 104-days drying shrinkage approximately 0.091% and 0.102% for FM1 and FM2, respectively. However, the rapid chloride permeability results were quite different. Because FM2 contains Class F fly ash, the average charge passed at 28-days was 1426 Coulombs, which meets the NJDOT limits of 2000 Coulombs. On the other hand, FM1 had moderate chloride ion penetrability. Thus, it is recommended that Class F fly ash be used in SCC to enhance its durability.

Table 8 - Compressive Strength (psi) (ASTM C39) for Fort Miller Mixes

Testing Day	FM 1	FM 2
3	5111	5211
7	5887	5569
14	6185	5887
28	6802	6165
56	7279	7041
90	NA	8274

Table 9 - Splitting Tensile Strength (psi) (ASTM C496) for Fort Miller Mixes

Testing Day	FM 1	FM 2
3	487	472
7	531	597
14	587	597
28	621	666
56	657	703
90	NA	682

Table 10 - Elastic Modulus (ksi) (ASTM C469) for Fort Miller Mixes

Testing Day	FM 1	FM 2
3	3186	3566
7	3633	3799
14	NA	3827
28	4102	3975
56	4115	3947
90	NA	4508

Table 11 - Rapid Chloride Permeability (Coulombs) (ASTM C1202) for Fort Miller Mixes

Testing Day	FM 1	FM 2
28	NA	1426
56	2504	959
90	NA	752

Table 12 - Average Length Change (%) (ASTM C157) for fort Miller Mixes

Testing Day	FM 1	FM 2
0	0.0000	0.0000
3	-0.0063	-0.0080
7	-0.0226	-0.0423
14	-0.0433	-0.0573
56	-0.0853	-0.0780
104	-0.0910	-0.1015

Laboratory Mixes

Because of the limited SCC mixes available for NJDOT, the research team, in coordination with NJDOT Staff, worked with two concrete producers that are approved by NJDOT to develop trial mixes that reflected local resources readily available in New Jersey.

The laboratory trial mixes included a minimum of four different SCC mixes include 1) Class A SCC using VMA, 2) Class A SCC using no VMA, 3) Class B SCC using VMA and 4) Class B SCC using no VMA. Several trial mixes of SCC were tested for compressive and modulus results.

Mix Proportions

A total of 8 mixes, consisting of one normal (or conventional) concrete, five SCC, and two HPC mixes, with w/b ratios ranging from 0.39 to 0.35 were made. This comparison of mix performance from each type of concrete allows the understanding of SCC in relation to HPC and Normal concrete.
Table 13 shows the mix proportions of all mixes. Normal Concrete (NC) mix represented the conventional concrete. Mix 1 represented the conventional concrete with 7000-psi compressive strength. SCC1 through SCC5 represented the five SCC mixes, and HPC1 and HPC2 represent the HPC mixes. All mixes had equal w/b ratio of 0.39, with the exception of SCC5, which had a w/b ratio of 0.35. The varying parameters between these mixes were the cementitious materials. Mix 1 contained only Portland Cement (PC); whereas, HPC1 and HPC2 mixes contained 20 % F and a combination of 5 % SF and 20 % F, respectively. For the SCC mixes, SCC1, SCC2, SCC3, and SCC4 had similar mix proportions with equal amounts of water, CA, and FA content, but they had varying cementitious materials. SCC1 contained only PC, whereas, SCC2, SCC3, and SCC4 contained 20 % F, a combination of 5 % SF with 20 % F, and 20 % SL, respectively. Additionally, the volume of the chemical admixture was adjusted for each mix to attain SCC characteristics. SCC5 was obtained from a precast plant as part of a field preliminary study for the New Jersey Department of Transportation (NJDOT) to deploy SCC in noise walls. SCC5 used different CA type and contained 20% Slag (SL) and VMA and color pigment was added to the mix.

The mixing procedure followed a modified ASTM C192 to account for the mineral and chemical admixtures as required by the manufacturer of the mineral and chemical admixture that required longer mixing time than conventional concrete. The mixing was performed in the laboratory using an electric drum mixer. Modifications to the ASTM C192 specification include: longer mixing time (rather than using the standard 3, 3, and 2 minutes mixing intervals, the mixing time was altered to 4, 4, and 5 minutes mixing intervals). The extended time was needed for the SL, SF, and F to evenly disperse in the concrete as well as for dispersing the SP, which was added during the final 5 minutes interval. Standard fresh concrete tests, such as the slump (ASTM C143) and air content test (ASTM C173), were also performed. However, for SCC, rather than using the standard ASTM slump test, a spread test was used as shown in Figure 1. The specimens were fabricated using a vibrating table for the Mix 1 and HPC mixes according to ASTM C192. For the SCC mixes, the concrete was simply poured into the molds without any consolidation. The specimens were sealed with a polythene sheet to minimize the loss of moisture.

Standard Laboratory Testing

The tests performed for SCC in this project are shown in Table 14. The concrete laboratory is fully equipped to test both normal and high performance concrete as well as large-scale structural concrete. Brief explanations for the tests are as follows:

Compressive Strength

The compression test was performed in accordance to ASTM C39 using the Forney-1 million pound compression-testing machine (Figure 5). The machine is equipped with three dial indicators for use at different loading ranges. In addition to the dial indicators, a 500-kip digital load cell was used to collect the data automatically through a computer-based data acquisition system. Compressive strength tests were conducted on all mixes at the age of 1, 3, 7, 14, 28, 56, and 90 days. All tests were performed using 4 × 8 in. cylinders that were moist cured in a water tank. For the compressive strength, three cylinders were loaded on each testing day in a compression machine. The test was performed in accordance with ASTM C39. The specimens' plainness was achieved by using unbonded steel caps with neoprene inserts for both the top and bottom ends of the specimens. The unbonded steel caps were used in lieu of the capping compound, in order to speed up the testing process.

Figure 5. Forney One-million lb Compression Testing Machine

Table 13 - Mix Proportions and Fresh Concrete Properties

Raw Material (lb/yd3)	Mixtures Identification							
	Mix 1	SCC1	SCC2	SCC3	SCC4	SCC5	HPC1	HPC2
OPC	806	870	696	652	608	566	646	605
SF	--	--	--	44	--	--	--	41
F	--	--	174	174	--	--	161	161
SL	--	--	--	--	260	144	--	--
CA	1727	1381	1381	1381	1381	1453	1727	1727
FA	1185	1496	1496	1496	1496	1354	1185	1185
Water	314	340	340	340	340	250	314	314
w/b	0.39	0.39	0.39	0.39	0.39	0.35	0.39	0.39
SP (oz)	60.8	146.8	100.1	120.1	68.4	80.4	38.4	57.6
AEA (oz)	2.4	1.3	2.0	1.3	1.3	11.6	12.9	12.9
VMA (oz)	--	--	--	--	--	20	--	--
Slump (in)	5.0	--	--	--	--	-	3.2	3.1
Slump Flow(in)	--	27.3	24.5	24.8	25.3	24.8	--	--
Air (%)	6	7	6	5	6	6	5	5

Table 14 - Summary of Laboratory Tests for SCC

Test	Routine of Tests	Applicable ASTM Standard	Curing Conditions	Age of Concrete at Test, days
1. Slump and Slump Flow	1 per batch	C143 and NJDOT C4 for Slump Flow	None	0, fresh
2. Fresh Air Content	1 per batch	C231	None	0, fresh
3. Unit Weight	1 per batch	C138	None	0, fresh
4. Compressive Strength	2 per batch & 4 per mix	C39	3, 28 day wet	1, 3, 7, 14, 28, 56,90
5. Split Cylinder Tensile Strength	4 per mix	C496	28 day wet	1, 3, 7, 14, 28, 56,90
6. Modulus of Elasticity	3 per mix	C469	28 day wet	1, 3, 7, 14, 28, 56,90
7. Air Dry Shrinkage	3 per mix	C490, C157	1 day wet	1 to 90
8. Air Void Analysis	1 per mix	C457	28 day wet	NA
9. Restrained Shrinkage	1 or 2 per mix	None	1 day wet	1 to 90
10. Freeze Thaw	3 per mix	C666	14 day wet	14
11. Scaling	1 per mix	C672	14 day wet plus 14 day dry	28
12. Rapid Chloride Permeability	3 per mix	C1202	28, 56, and 90 days	28, 56, and 90

Modulus of Elasticity

The elastic modulus is performed in accordance to ASTM C469 using a compressometer. The compressometer is equipped with digital dial gage that has an accuracy of 0.00005 in., which is sufficient for this test. The modulus of elasticity test was conducted in accordance with ASTM C469. Unlike the compression test, rather than using unbonded steel caps, the top and bottom of the cylinder were covered with capping compound. The strain was measured using the average of three linear variable differential transformers (LVDTs) that were attached to a compressometer (Figure 6).

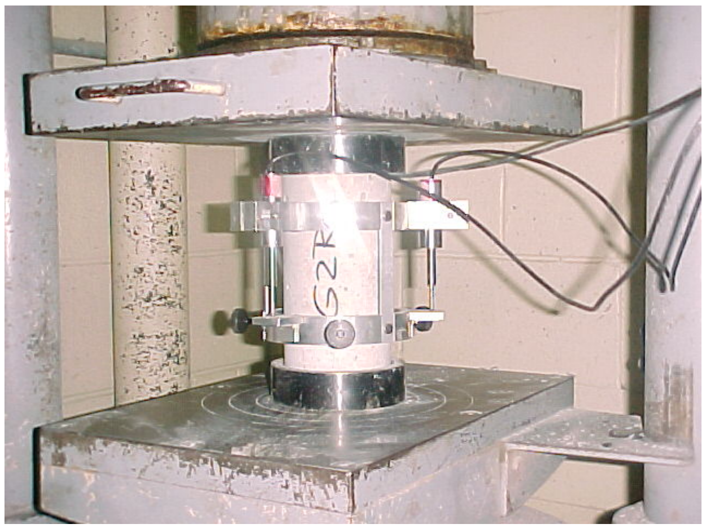


Figure 6. Elastic Modulus Test Using 3-LVDT Ring

Splitting Tensile Strength

Splitting tensile strength is determined by splitting a 4 X 8 in. cylinder in accordance to ASTM C496 using the 400-kip Tinius Olsen compression-testing machine. The Tinius Olsen Compression machine (Figure 7) is used because it has longer head extension than the Forney 1-million pound compression machine. On each testing day, three 4 × 8 in. cylinders were loaded along the length in the compression machine. To avoid localized cracking and to ensure that the load is distributed uniformly, thin sheets of plywood with a width of 1 in. and thickness of 1/8 in. were placed between the top and bottom load bearings.

Figure 7. Tinius Olsen Compression-Testing Machine

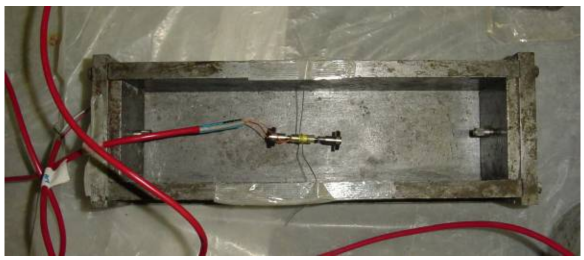
Drying Shrinkage

Drying shrinkage of concrete is determined in accordance with ASTM C157 using a length comparator and/or vibrating wire strain gage (VWSG) embedded inside the concrete prism. Figure 8a and 8b illustrate the drying shrinkage measurements using length comparator and VWSG, respectively. The drying shrinkage specimens consisted of three 3 × 3 × 11 in. prisms with embedded studs at each end. The drying shrinkage was measured using a length comparator (a) where the length of the concrete (between the two embedded studs) was compared to a reference bar. After the concrete was cast, all specimens were carefully wrapped in plastic to avoid moisture loss. After 24 hours, the specimens were de-molded and stored in an environmental chamber with a controlled ambient temperature and relative humidity of 75^{o}F and 50%, respectively. The drying shrinkage was measured at 1, 3, 7, 14, 28, 56, and 90 days using the length comparator.

Creep

Creep test is performed in accordance to ASTM C512 using spring loaded creep frame (creep rig). The concrete strain is measured by external vibrating wire strain gages. The external strain gages are instrumented on the specimens at three gage lines spaced uniformly around the periphery of the specimen. For each creep test, a total of 5 specimens are instrumented, 3 specimens are used for loading and the other 2 are used as control specimens. The vibrating wire strain gages are connected to two 96 channels data logger that record the strain value at every 10 minutes. The applied load is monitored with a 200 kip load cell that is also connected to the data logger. The creep test setup is illustrated in Figure 9.

(a)



(b)

Figure 8. Drying Shrinkage Test Setups: a) Length Comparator, b) VWSG Setup

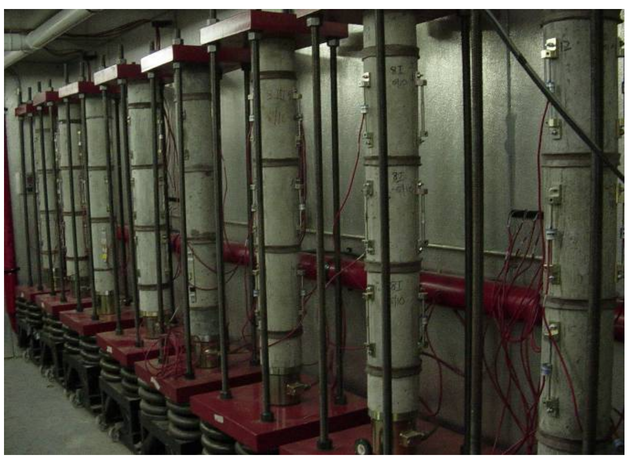


Figure 9. Creep Rig Test Set-up

Rapid Chloride Permeability Test

The rapid chloride permeability test (RCPT) was performed at 28, 56, and 90 days in accordance with ASTM C1202. Three 4 × 8 in. cylinders were used for each mix. The cylinders were sliced into three layers of equal length of 2 in. The RCPT was conducted by measuring the current every 30 minutes for 6 hours. The charge passed corresponds to the integration of the area under the curve of the current versus time relationship. A correction factor was applied to the charge passed since the diameter of the specimens was not the standard 3 in. of cored specimens. Figure 10 illustrates the RCPT setup.

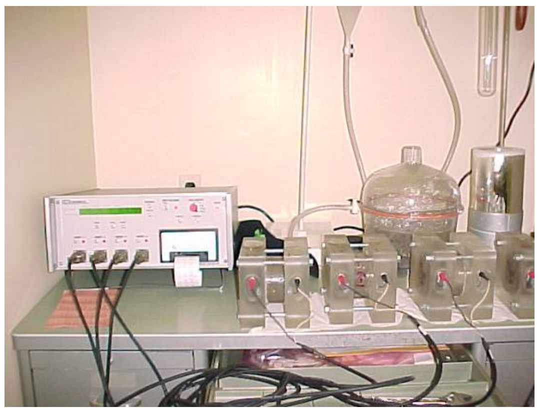


Figure 10. Rapid Chloride Permeability Test Setup

Results

The test results of the fresh concrete properties are shown in Table 13. Spread diameters, slump, and air content are tabulated for all mixes. There was a significant effect on the fresh concrete properties with the addition of the pozzolans. Both fly ash (F) and slag (SL) significantly reduced the water demand of concrete and, therefore, lower the amount of superplasticizer needed. On the other hand, silica fume (SF) increased the water demand of the mix; however, because of the presence of fly ash, the mix still required less superplasticizer than the regular SCC mix (SCC1). Nevertheless, the mix containing fly ash did require more AEA than the other mixes. The spread diameter of SCC mixes varied from 24.5 in. to 27.5 in. Values greater than 24 in. indicate good flowability as well as good ability to self consolidate without segregation.

Table 15 illustrates the comparison of the mechanical properties of all laboratory mixes including the HPC mixes. Figure 11 illustrates the comparison of compressive strengths of normal/conventional concrete (NC) and SCC1 mix with their elastic moduli and splitting tensile strengths. It can be seen that the rate of increase of compressive strength of both NC and SCC mixes are higher than the rates of moduli and tensile strengths. More importantly there is no significant difference between the mechanical properties of NC and SCC1.

Figure 12a shows the compressive strength and modulus of elasticity of mixes SCC1, SCC2, SCC3, and SCC4. Figure 12b shows the compressive strength and tensile splitting strength of the same mixes. The SCC mix containing F only (i.e., SCC2) had the highest compressive strength, modulus of elasticity, and tensile splitting strength compared to all other SCC mixes. The increase was approximately 5% compared to SCC containing OPC only (i.e., SCC1). Both SCC3 and SCC4 had the worst performance with a minimum of 15 % reduction in compressive strength, modulus of elasticity, and tensile splitting strength at early-age when comparing to SCC1. At later-age, both SCC3 and SCC4 still had lower compressive strength and tensile splitting strength with a minimum of 5 % reduction, but have comparable modulus of elasticity with SCC1. In other words, the addition of pozzolans does not seem to have a long-term effect on the mechanical properties of SCC.

Figure 13a shows the compressive strength and modulus of elasticity of the SCC mixes with varying w/b ratios and Figure 13b shows the compressive strength and tensile splitting strength for the same mixes. As expected, the mix containing lower w/b ratio (i.e., SCC5) had higher compressive strength and tensile splitting strength than mix containing higher w/b ratio (i.e., SCC4). However, mix SCC4 had higher modulus of elasticity than mix SCC5. This could be attributed to the fact that mix SCC5 was obtained from the precast plant and had different type of CA and lower cement content. In addition, mix SCC5 had different chemical admixtures including VMA and added color pigment.

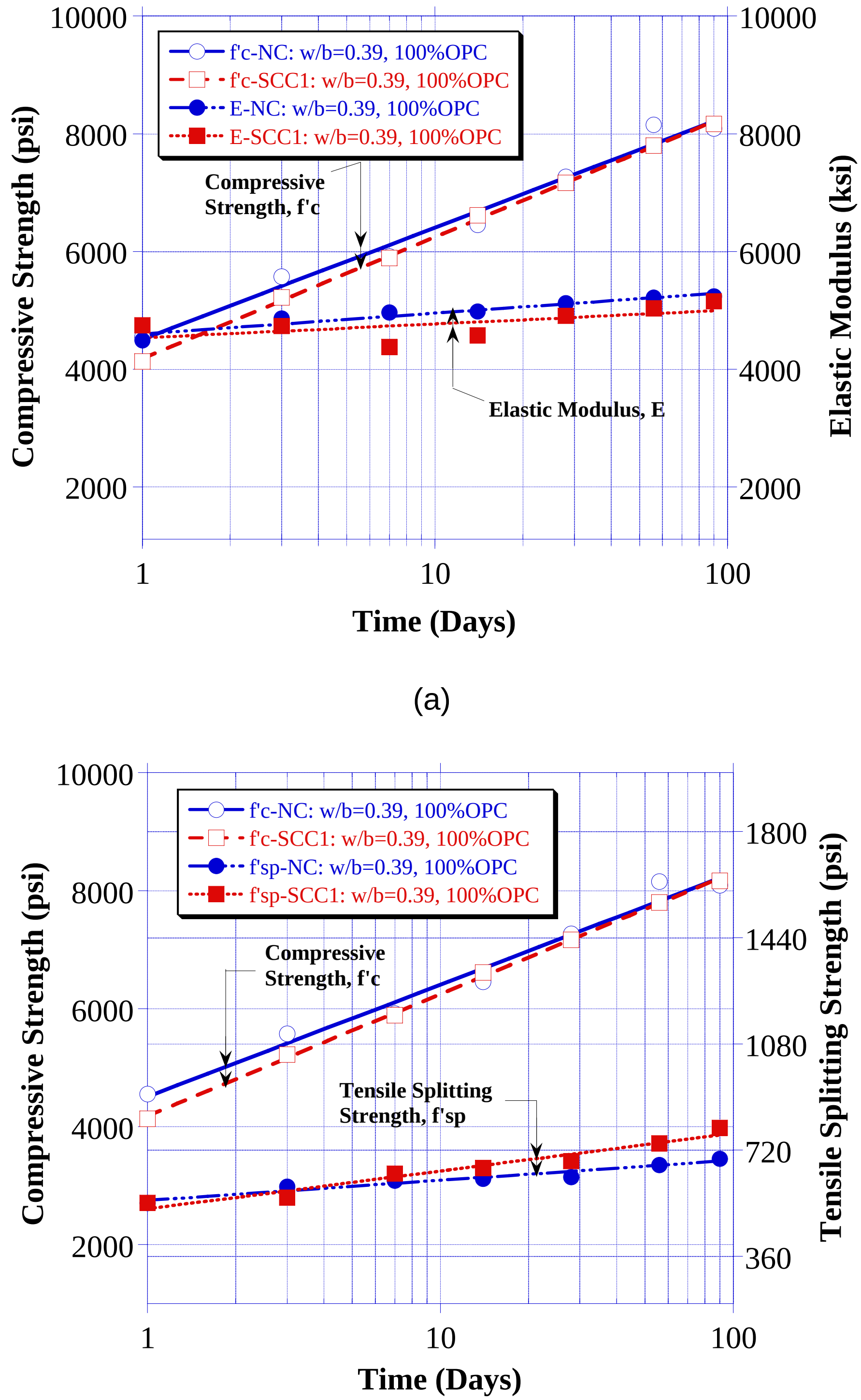
Figure 14a and Figure 14b show the relationship of the compressive strength and modulus of elasticity between SCC and HPC mixes. It is observed that SCC mixes outperformed HPC mixes in terms of modulus of elasticity, i.e., SCC2 had an average of 8 % increase over HPC1; and SCC3 had an average of 6% increase over HPC2.

Figure 15 illustrates the drying shrinkage of normal/conventional concrete, SCC, and HPC mixes. It is observed that the HPC mixes had the lowest drying shrinkage, whereas the SCC mixes had the highest drying shrinkage. The reason for this is because SCC mixes had higher cementitious paste and higher capillary pores that lead to higher drying shrinkage. Nevertheless, the shrinkage subsided as pozzolans were added to the SCC mixes. Among all the SCC mixes, the mix containing both SF and F has the lowest drying shrinkage with a 20 % reduction in comparison with the SCC1 or regular SCC mix. Mix SCC2 (or SCC mix containing 20 % F) also had a 10% reduction, whereas, SCC3 (or SCC containing 30 % SL) did not have a significant reduction.

Table 15 - Comparison of Mechanical Properties of Laboratory Mixes

Time (Days)	Compressive Strength (psi)							
	Mix 1	SCC1	SCC2	SCC3	SCC4	SCC5	HPC1	HPC2
		(PC)	(%20FA)	(%5SF+ %20FA)	(%20SL)	(%20SL)		
1	4554	4134	4279	3031	2872	4728	2814	3234
3	5569	5221	5816	4279	4192	6309	4250	4250
7	5918	5889	6933	5018	5221	6991	5221	4772
14	6454	6614	6947	5439	5918	8789	5656	5961
28	7266	7165	7513	5874	6150	8702	6411	6672
56	8151	7803	8398	7005	6556	9007	7397	7194
90	8093	8166	8963	7136	6338	8963	8137	7774
Time (Days)	**Modulus of Elasticity (KSI)**							
1	4493	4746	3904	2983	3314	2659	3656	3441
3	4863	4733	4332	3944	3685	3274	3782	3483
7	4963	4379	4830	3789	3960	3030	4287	3652
14	4981	4576	4758	4483	4408	3792	4211	3875
28	5120	4906	4880	4672	4835	4535	4589	4020
56	5215	5035	5233	4735	4878	4499	5026	4187
90	5236	5155	5946	4475	5060	4277	5558	4390
Time (Days)	**Tensile Splitting Strength (psi**							
1	537	537	522	377	421	537	N/A	N/A
3	595	566	609	435	464	566	N/A	N/A
7	624	638	682	508	522	609	N/A	N/A
14	624	667	696	566	551	638	N/A	N/A
28	624	682	725	580	580	769	N/A	N/A
56	667	740	856	653	609	783	N/A	N/A
90	696	798	798	667	653	798	N/A	N/A

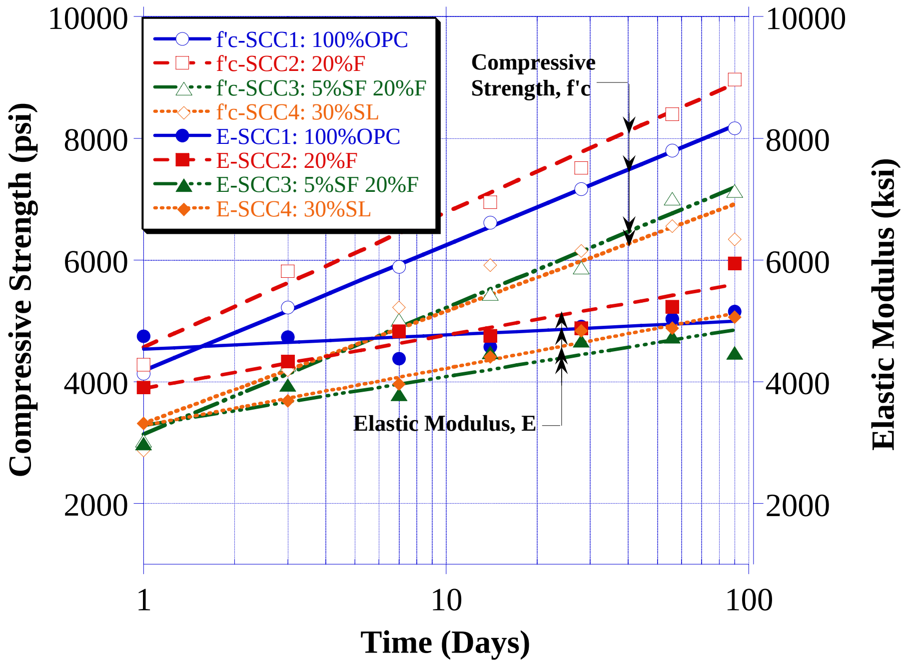
* The slump of the SCC mixes is the average spread.



(a)

(b)

Figure 11. Comparison of Compressive Strength and a) Modulus of Elasticity, b) Tensile Splitting Strength of Mix 1 and SCC1 Mixes



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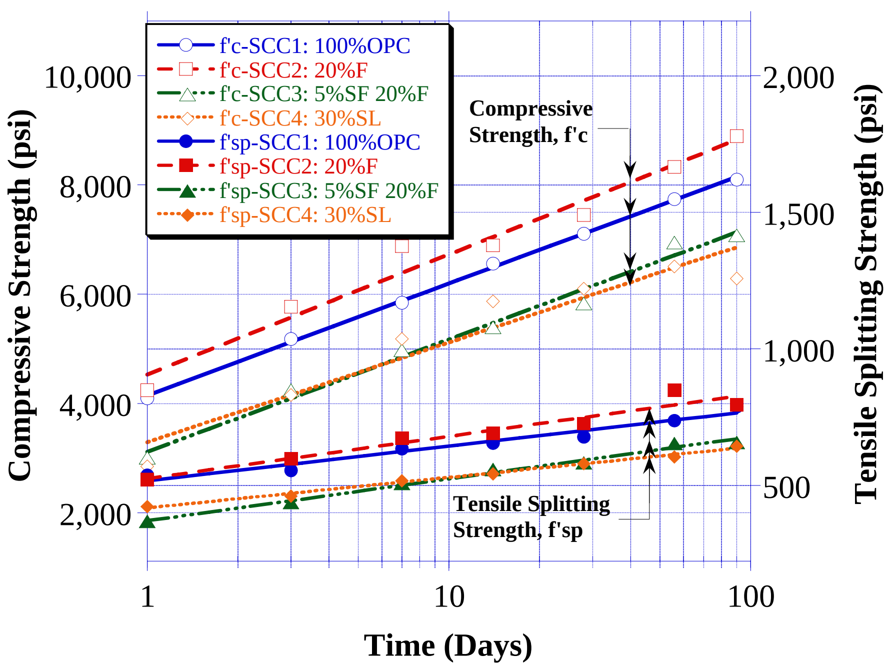
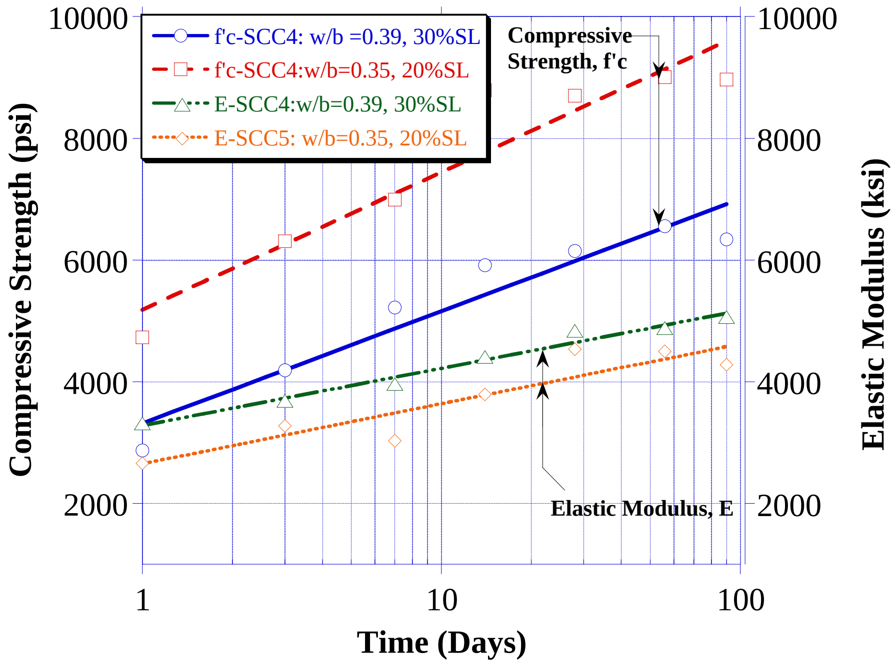
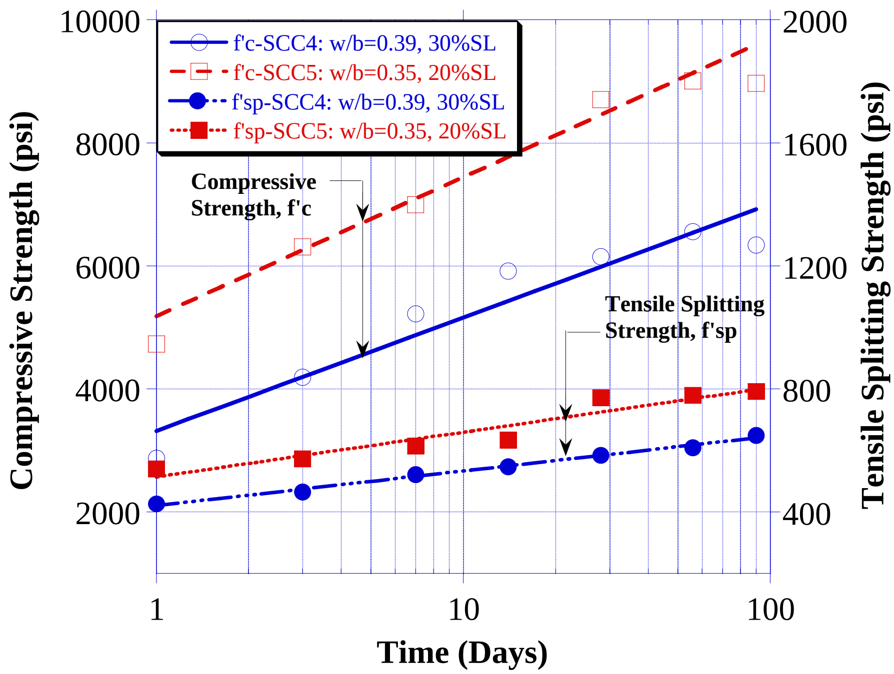


(b)

Figure 12. Comparison of Compressive Strength and a) Modulus of Elasticity, b) Tensile Splitting Strength of SCC Mixes

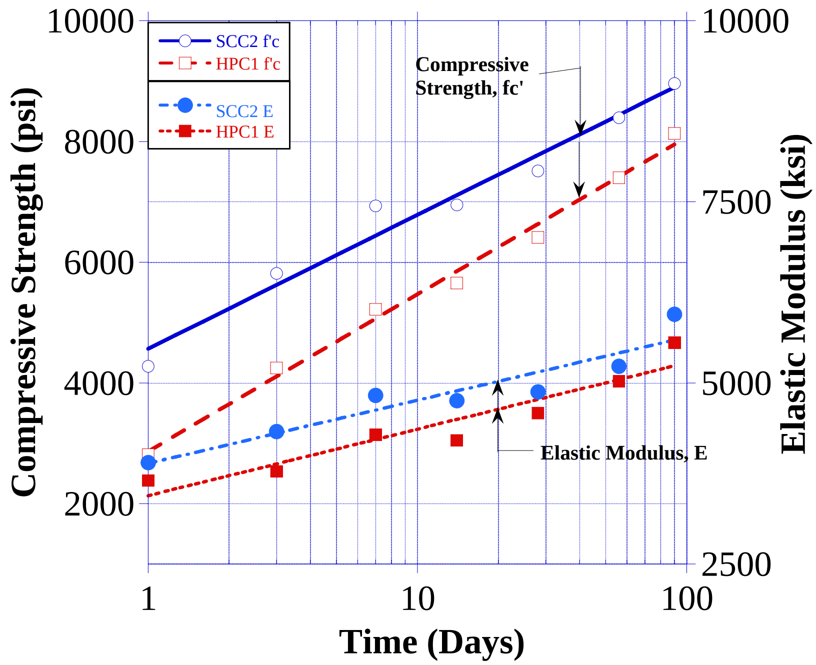


(a)

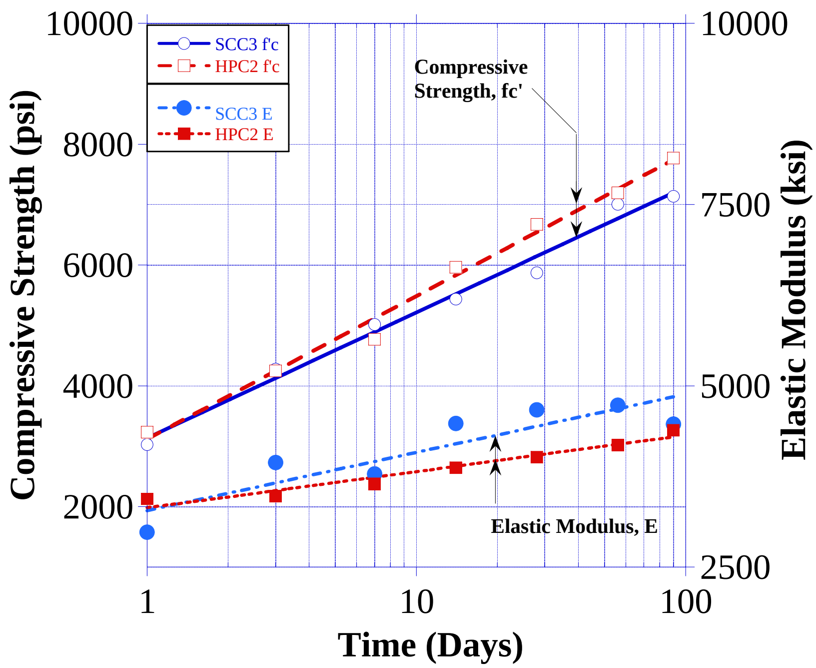


(b)

Figure 13. Comparison of Compressive Strength and a) Modulus of Elasticity, b) Tensile Splitting Strength of SCC4 and SCC5 Mixes



(a)



(b)

Figure 14. Comparison of Compressive Strength and Modulus of Elasticity of SCC and HPC Mixes containing (a) 20% F and (b) 5%SF 20%F

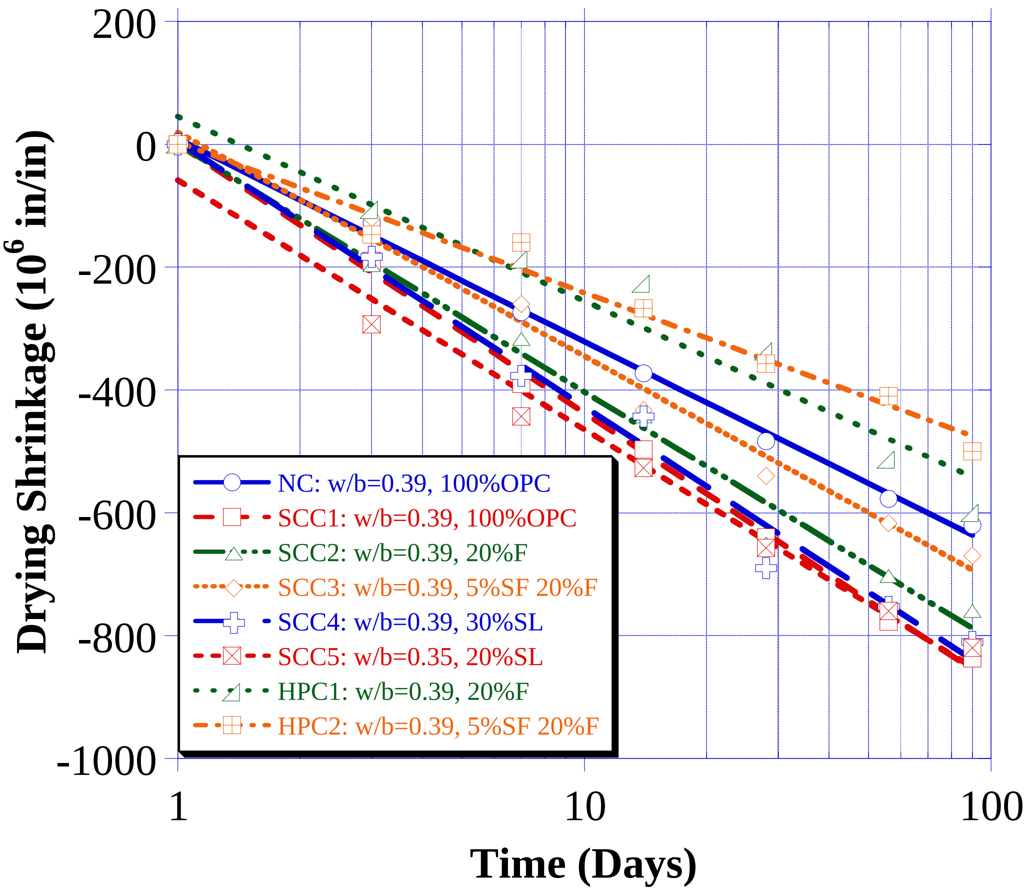


Figure 15. Comparison of Drying Shrinkage of All Mixes

Figure 16 shows the rapid chloride permeability test (RCPT) results for all mixes. It is observed that there is a significant variation in the RCPT charge passing rates among normal/conventional concrete, SCC, and HPC. The SCC mixes had significantly higher "charge-passed" values at all testing days. This is attributed   to the increase in paste volume that leads to higher capillary voids. The added supplementary cementitious materials (with the exception of SL) also had a significant effect on the RCPT. Figure 16 shows that SCC with Pozzolans had about 30 % reduction in the charge-passing rate compared to the regular SCC. The combination of SF and F seems to have the most influence on the permeability with a 57 %, 74 %, and 81 % reduction at 28, 56, and 90 days, respectively, over SCC with PC. The added SF also reduces the permeability of SCC containing F by approximately 50%. The reason for this reduction is that SF is highly reactive and has a high surface area, allowing it to fill the capillary pores and making the concrete denser and less permeable. In addition, as expected, both HPC mixes outperform all other mixes in the RCPT test.

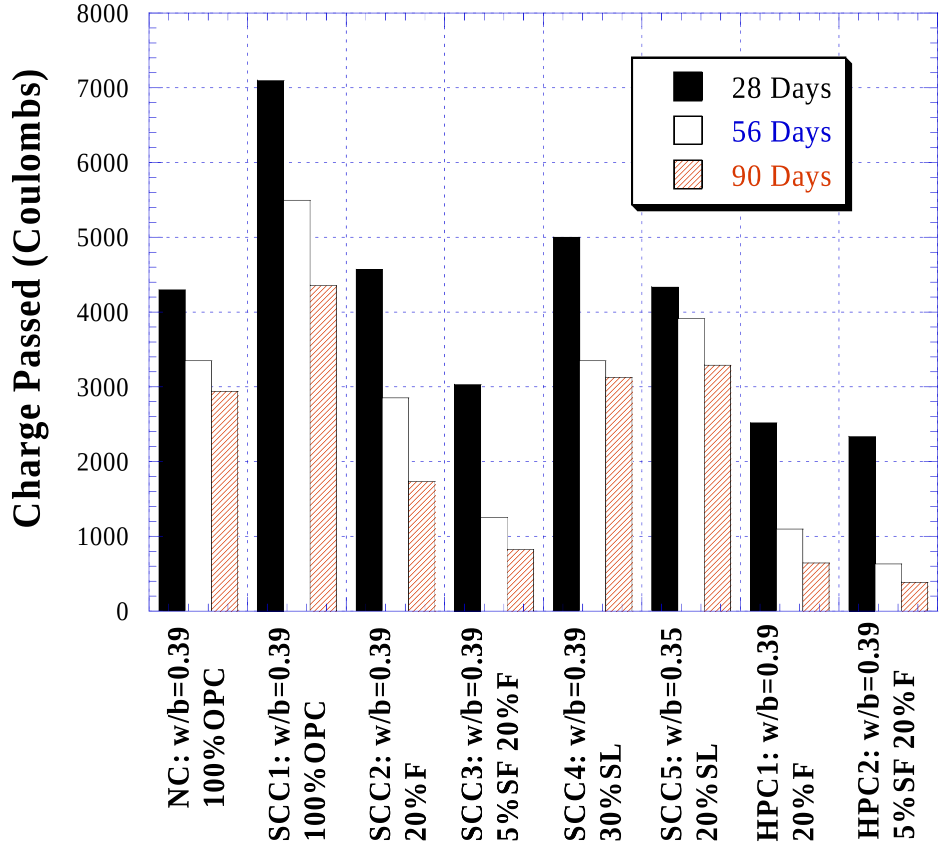
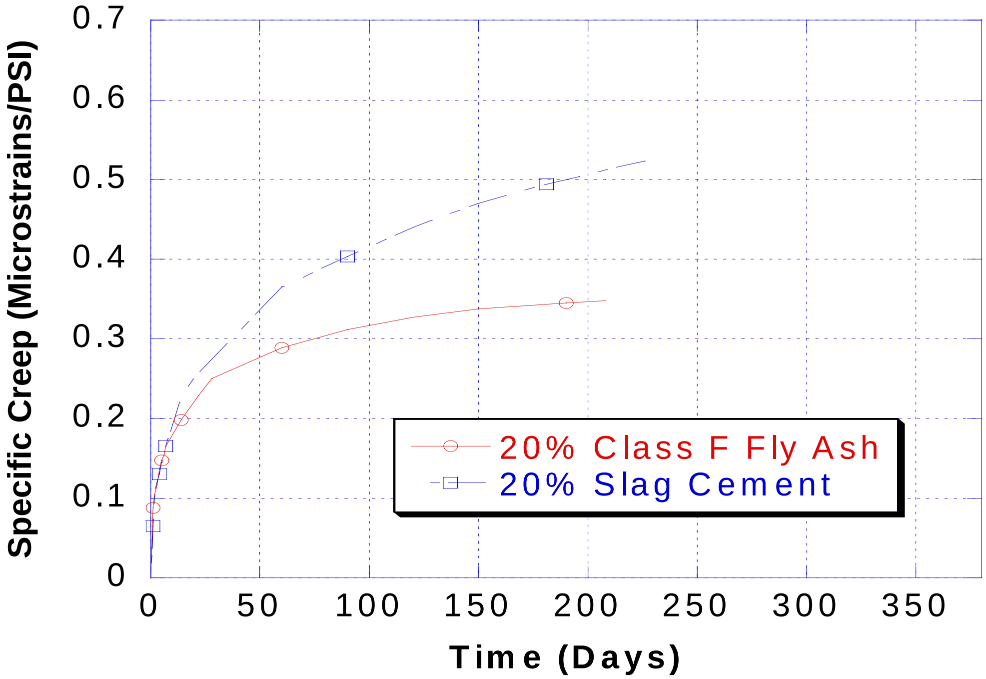
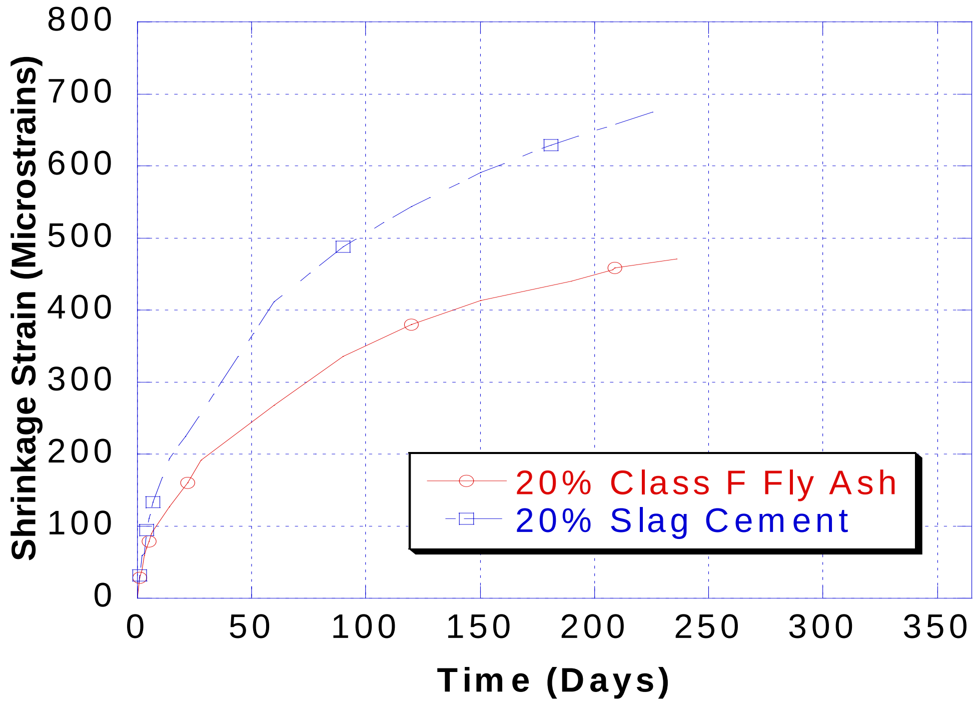


Figure 16. Results of Rapid Chloride Permeability Tests of All Mixes

Figure 17a and Figure 17b illustrate the specific creep and shrinkage of SCC containing slag cement and class F fly ash, respectively. The SCC mix containing 20% Class F fly ash (SCC2) has lowered specific creep and shrinkage than the SCC mix containing 20% slag cement (SCC5). Thus, it is recommended that Class F fly ash be used when the structural components where lower creep and shrinkage are desired.



(a)



(b)

Figure 17 Plot of (a) the Specific Creep and (b) Shrinkage of SCC Containing 20% slag cement and 20% Class F Fly Ash

PHASE II - DRILLED SHAFT INSTRUMENTATION AND FIELD SAMPLING

Phase II of the SCC project consisted of constructing drilled shafts with SCC on I-280 Interchange Project located in Newark, NJ, field instrumentation and monitoring of the shafts, and collecting concrete specimens. The work on this project started in November of 2006 and the drilled shaft construction was completed in mid 2007. The Research Team worked with the contractor and the NJDOT resident engineer on coordinating the instrumentation and collection of field samples during the construction of the drilled shafts. Two SCC Shafts from the project and a demonstration shaft were instrumented with vibrating wire strain gages to monitor load effects and temperature. Results from drilled shaft testing (including the standard cross-holes sonic logging (CSL) performed by the Contractor) were used to evaluate shaft integrity similar to the other shafts of the project.

Testing and Field Sampling of Demonstration Drilled Shaft

The drilled shaft was instrumented with five Geokon Model 4200 Concrete Embedment Gages to monitor the temperature and strains during and after construction. In addition to measuring the concrete strain, the gage is also equipped with a thermistor to measure the temperature. Table 17 and Figure 18 illustrate the sensor locations inside the drilled shaft. Figure 19 and Figure 20 show the concrete embedment gage attached to the cage and the cage lowered down into the drilled shaft, respectively. Figure 21 shows the data acquisition system used to collect data at 5-minutes interval from all sensors starting from the time of pour.

Concrete Field Sampling and Laboratory Testing

Twenty 4 x 8 inch and three 6 x 12 inch concrete cylinders were taken at the day of the concrete pour from the second of five trucks that were assigned for the job. The specimens taken were to be used to test the compressive strength as well as the modulus of elasticity of the mix at different ages. The 6 x 12 cylinders were also used to confirm the results form the other cylinders at 28 days. Table 16 shows the results of the compressive strength tests performed on the field mix at various ages.

Table 16 - Compressive Strength of Demonstration Shaft Field Mix (psi)

Day	Date	Specimen 1	Specimen 2	Specimen 3	Specimen 4	**Average**
3	14-Dec-06	3858	3819	3739	N/A	**3805**
7	18-Dec-06	4893	4893	4694	N/A	**4826**
14	25-Dec-06	4893	5211	3819	4535	**4614**
28	8-January-07	5091	5489	5728	5052	**5340**

Results show that at days 3 and 7 all specimens failed in shear and the individual test results were close to each other. However, due to the higher variation of results observed on days 14 and 28, additional samples were tested. It was observed that a number of the samples failed by crushing of the top or bottom of the cylinder specimen prematurely and prior to reaching the expected crushing load. This failure type is believed to occur due to the accumulation of paste at the top of the sample as a result of segregation.

Table 17 - Sensor Locations

Sensor ID	Distance from Top (ft)
Sensor 1	0.25
Sensor 2	1
Sensor 3	16.75
Sensor 4	16.75
Sensor 5	32.5

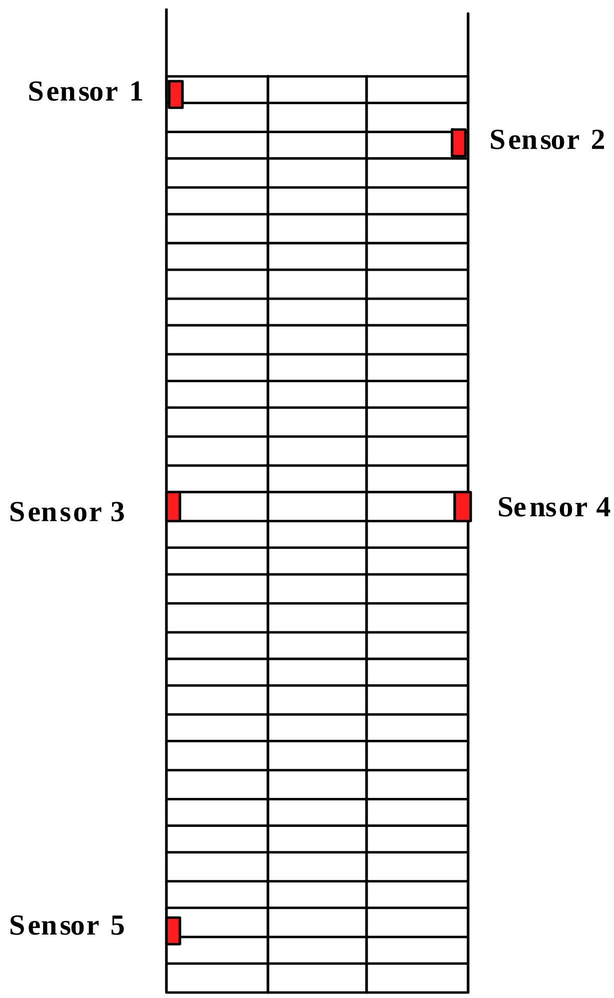


Figure 18. Sensor Locations (Not to scale)

Two 6 x 12 inch cylinder specimens were also tested to confirm the 28-day compressive strength results from the 4 x 8 inch cylinders. First specimen had a failure stress of 6119 psi with a shear type failure and the second specimen failed as seen in Figure 22 at a value of 5305 psi, with an average value of 5712 psi. Figure 22 illustrates the failure mechanism observed while testing specimen 4 at 28-day tests. As described earlier the failure takes place by crushing of concrete on the top (or bottom) of the specimen. The bottom part of the cylinder crumbled slowly into many pieces until the specimen could not sustain any more load.

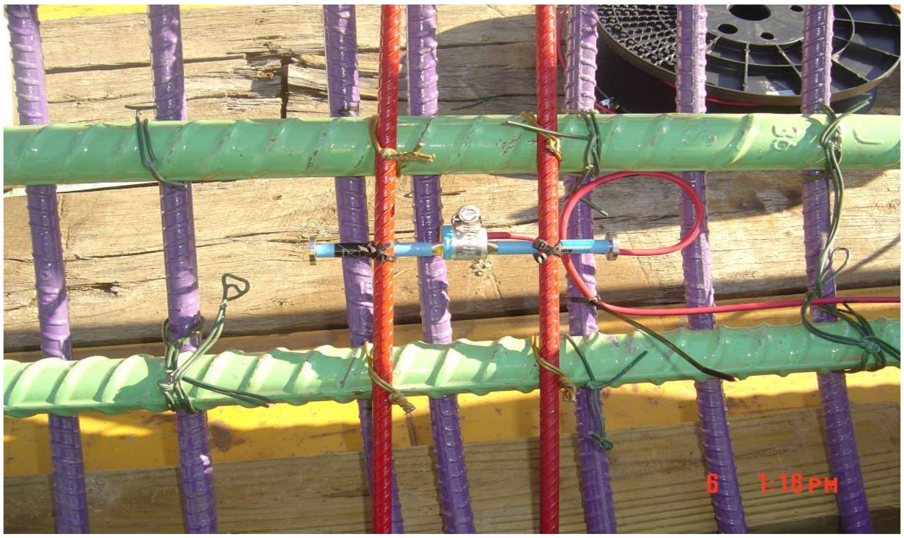


Figure 19. Model 4200 Concrete Embedment Gage

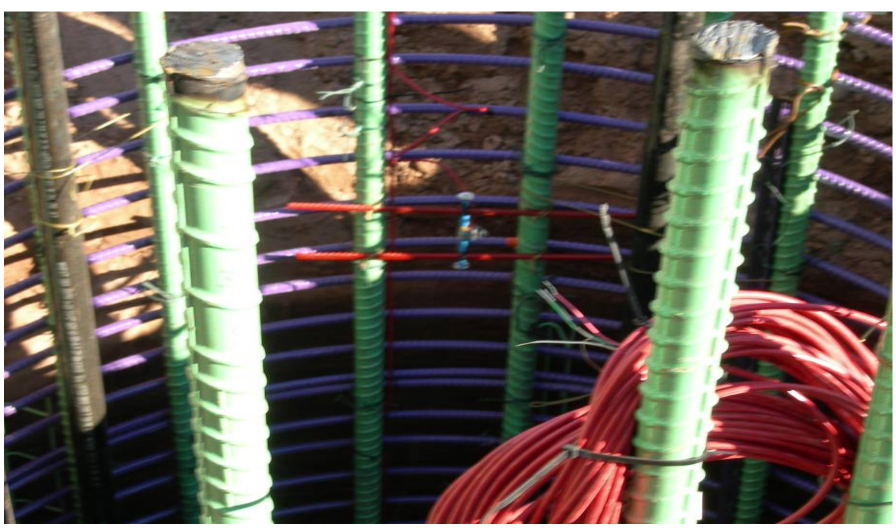


Figure 20. Model 4200 Gage After Cage Placement

Figure 21. Data Acquisition System

Figure 22. Failure Type of Demonstration Shaft Concrete Under Compression

Figure 23 illustrates the picture that was taken before the specimens were capped by a high strength sulfur compound. The top ¼ in portion of the sample was observed to be almost entirely composed of cement paste with many air pockets. This is mostly due to the segregation of the concrete and it is the main cause for high variation in the compressive strength tests.

Figure 23. Top View of 6 x 12 inch Test Specimen

Strain and Temperature Profile

Figure 24 and Figure 25 show the change in strains and temperature from the time of pour (December 11, 2006) to 28 days (10:25 am January 8, 2006), respectively. Sensors 3 and 4 recorded temperature values around 63 ^{0}F. This is expected since these sensors are in the middle of the shaft. Dissipation of the heat of hydration is therefore much slower than the concrete near the top surface (which is exposed to ambient temperatures) and the concrete that is close to bottom (which dissipates heat through contact with the surrounding soil). The initial temperature recorded by the gages is the temperature of the concrete at the time of arrival of the truck to the site. This value is around 75 ^{0}F for all sensors. Peak temperature of Sensors 1 and 2 are 106 ^{0}F and 94 ^{0}F, respectively. For Sensors 3 and 4 the values were 126.5 ^{0}F and 128 ^{0}F, respectively, while the value for Sensor 5 was 111 ^{0}F. Strains in all sensors are in compression indicating that the concrete is shrinking freely.

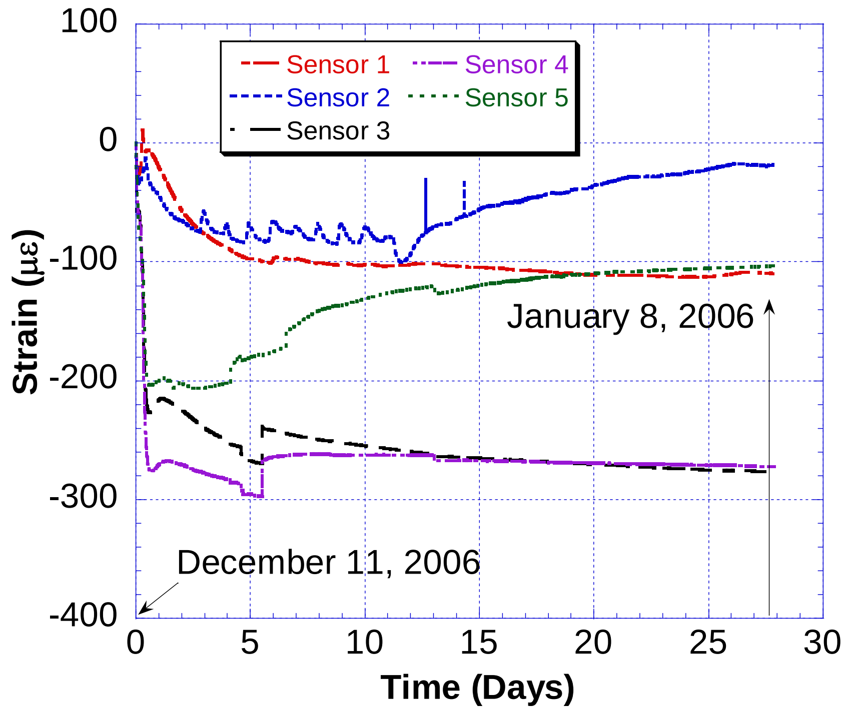


Figure 24. Strain Profile of the Demonstration Shaft

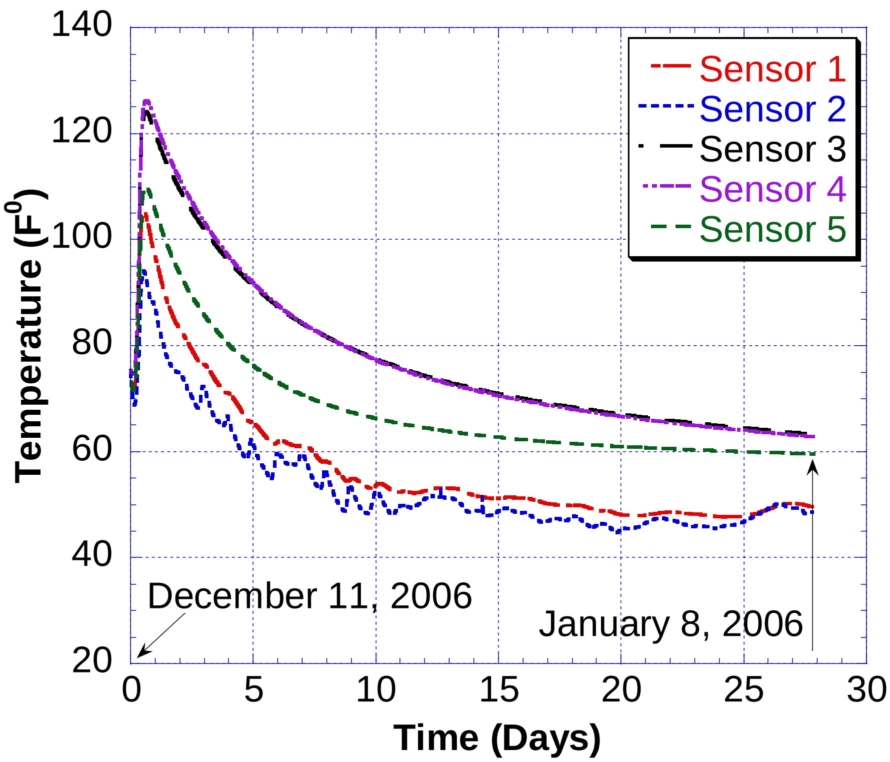


Figure 25. Temperature Profile of the Demonstration Shaft

Testing and Field Sampling of Drilled Shaft #3

Drilled Shaft #3 is the 2^{nd} out of 3 of the drilled shafts that were poured for the Route 280 project. Similar instrumentation and field sampling procedures were followed as was performed in the demonstration shaft. The number of samples taken was increased to test for other mechanical properties such as tensile strength and modulus of elasticity. Moreover, on top of regular slump flow tests performed, L-box and J-ring tests were also utilized to test the flowability of the SCC supplied to the site.

Instrumentation

The drilled shaft was instrumented with 3 embedment concrete strain gages that also have thermistors attached. The total length of the shaft was 33 ft with only 20 ft being under ground. Two sensors were placed at mid-height whereas the other sensors were placed one foot above the bottom of the shaft. Figure 26 and Figure 27 show drilled shaft #3 and close-up view of the sensors installed, respectively. The shaft was monitored for 14 days and then the data logger unit was moved to drilled shaft #1.

Fresh Concrete Properties

Table 18 summarizes the fresh concrete testing results for Drilled Shaft #3 and Figure 28 through Figure 33 illustrate the field-testing procedures. Due to space limitations at the location of the drilled shaft concrete pours, not all tests were performed for each truck. However, the slump flow test was performed for every truck arriving at the site. The value of the slump flow test from the truck No. 1 was higher in comparison with those from other trucks. According to the results of the J-Ring test, the concrete from Truck No. 1 will have minimal to noticeable blocking while the concrete from Truck No. 3 will have no visible blocking. The L–Box test performed on the concrete from Truck No. 4 indicated that blocking may be experienced since h_2/h_1 was observed to be less than 0.9.

Table 18 - Fresh Concrete Tests Performed on Concrete for Drilled Shaft #3

Truck No.	Slump Flow (in)	J-Ring Flow (in x in)	Difference from Slump Flow (in)	L - Box		
				h_2 (in)	h_1 (in)	h_2/h_1
1	28.5	27	1.5	-	-	-
2	24.5	-	-	-	-	-
3	18.5	18.25	0.25	-	-	-
4	19.5	-	-	3.25	4.75	0.684

Figure 26. Drilled Shaft #3

Figure 27. Close-up View of the Sensors in Drilled Shaft #3

Figure 28. Slump Flow Test

Figure 29. Slump Flow

Figure 30. J-Ring Flow Test

Figure 31. J-Ring Flow Measurement

Figure 32. L-Box Test

Figure 33. L-Box Test Measurement (h_2)

Mechanical Properties

Table 19 illustrates a summary of the mechanical properties of the concrete obtained from Drilled Shaft #3. It is observed that the average compressive strength at 28 days is 35 percent higher than those obtained from testing the concrete specimens collected from the demonstration shaft. During testing, it was also observed that none of the samples experienced premature failures due to segregation. This is believed to be due to the lower slump flow obtained from drilled shaft #3 mix.

Table 19 - Mechanical Properties of Concrete from Drilled Shaft #3

Day	Compressive Strength (psi)	Splitting Tensile Strength (psi	Modulus of Elasticity (ksi)
3	3839	514	-
7	5542	622	3651
14	6086	595	4070
28	7823	671	4100
56	7902	723	4320

Temperature and Strain Profile

Figure 34 and Figure 35 illustrate the strain as well as the temperature profiles for Drilled Shaft # 3, respectively. Sensors 1 and 2 were placed at mid-height where as sensor 3 was placed at the bottom of the drilled shaft.

Testing and Field Sampling of Drilled Shaft #1

Drilled Shaft #1 was the last of the four shafts that were poured for the Route 280 Project. The numbering scheme and arrangement of the sensors used was identical to that used in Drilled Shaft #3 and the same field tests were employed on two of the four trucks that arrived to the site.

Instrumentation

As was done in the other drilled shafts, two sensors were installed at the mid-height of the shaft whereas the last sensor was placed close to the bottom of the shaft. The readings from the sensors were monitored up to 14 days only.

Fresh Concrete Properties

Table 20 shows the results of the fresh concrete tests performed on two of the four trucks that arrived to the site for Drilled Shaft #1. The slump flow values from both trucks varied between 19 and 21.5 inches, which is less than the limit of 24 inches specified by NJDOT Specifications. The J–Ring test performed on the second truck (measured flow is 21.5 inch.) indicated that blocking should be observed in the concrete from this truck. The L–Box readings correlated well with the J-Ring test results showing that blocking might be obtained due to the h_2/h_1 ratio of 0.632, which is lower than the L–Box test limit 0.9.

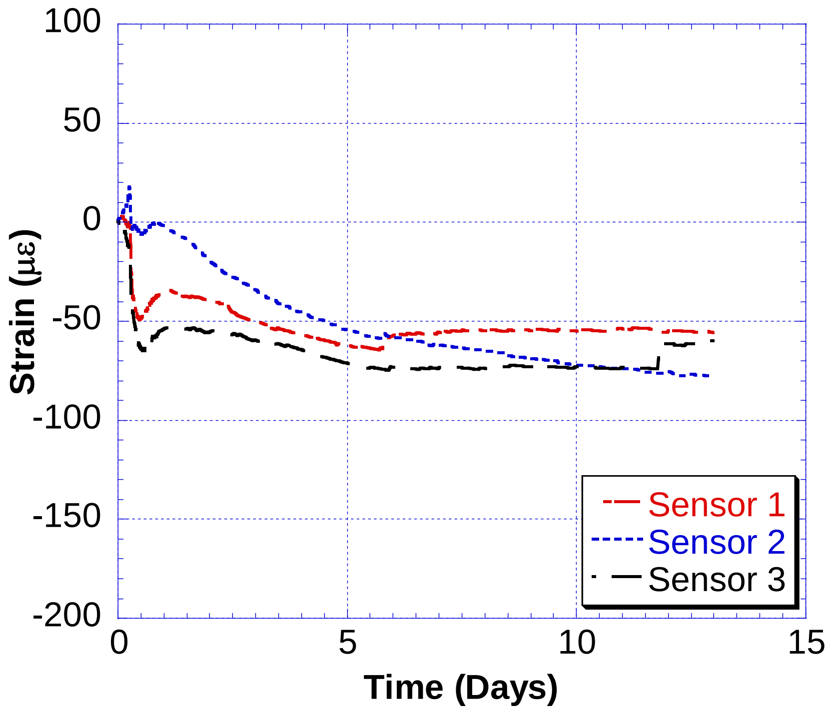


Figure 34. Strain Profile in Drilled Shaft #3

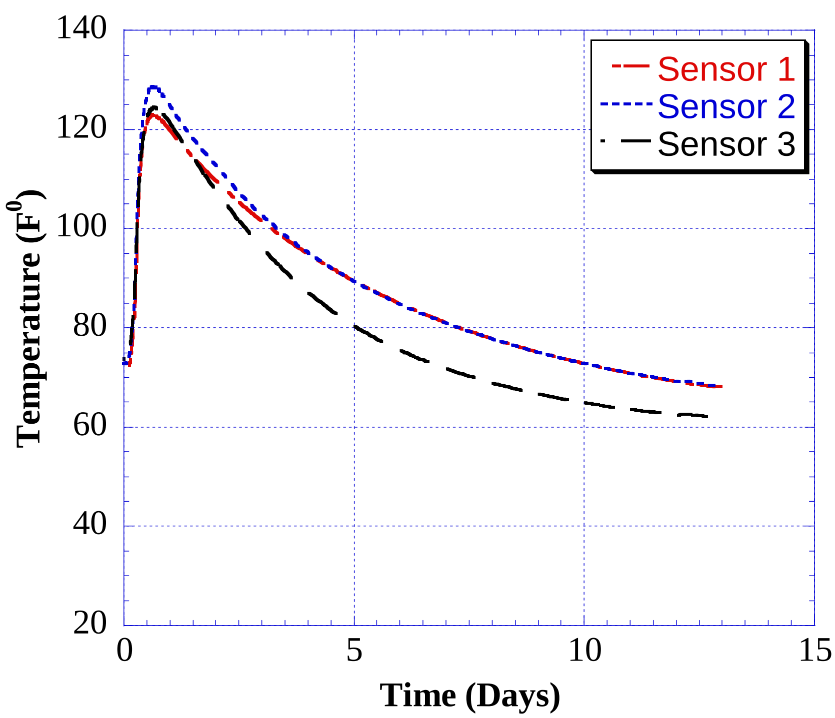


Figure 35 Temperature Record in Drilled Shaft #3

Table 20 - Fresh Concrete Tests Performed on Concrete for Drilled Shaft #1

Truck	Slump Flow (in)	J-Ring Flow (in x in)	Difference from Slump Flow (in)	L - Box		
				h_2 (in)	h_1 (in)	h_2/h_1
1	19	-	-	-	-	-
2	21.5	21.5	0	3	4.75	0.632

Mechanical Properties

Table 21 summarizes the mechanical properties of the concrete obtained from Drilled Shaft #1. It can be seen that all tests had very similar results to those from Drilled Shaft #3. The only noticeable difference is in the modulus of elasticity in which Drilled Shaft #1 has higher values in comparison with those obtained from tests on Drilled Shaft #3.

Table 21 - Mechanical Properties of Concrete from Drilled Shaft #1

Day	Compressive Strength (psi)	Splitting Tensile Strength (psi	Modulus of Elasticity (ksi)
1	1774	288	-
3	4037	526	3774
7	5708	586	4327
14	6616	652	4528
28	7425	667	4661
56	7836	749	4701

Temperature and Strain Profile

Figure 36 and Figure 37 show the strain as well as the temperature profiles for Drilled Shaft # 1, respectively. Sensor 1 is at the bottom of the shaft whereas the remaining two sensors are in the mid-height of the shaft. It is observed that the temperatures and the strains are identical to the strains and temperatures obtained from the other two shafts.

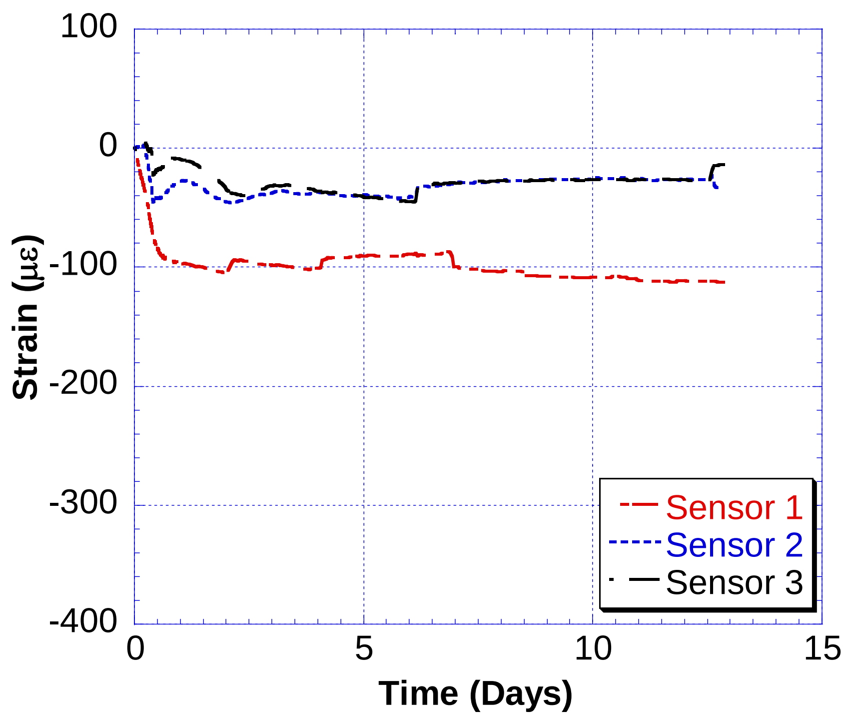


Figure 36. Strain Profile in Drilled Shaft #1

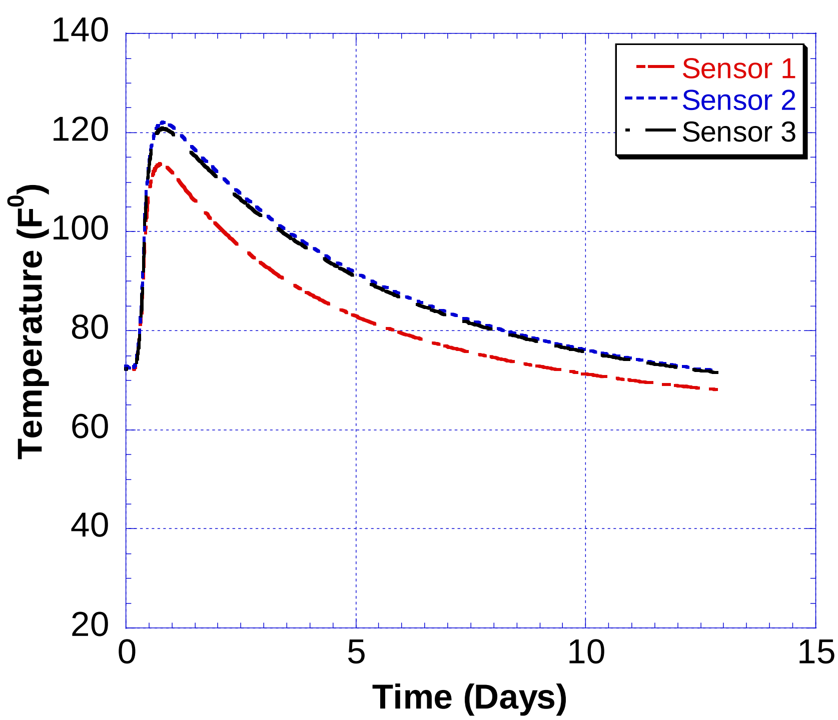


Figure 37. Temperature Profile in Drilled Shaft #1

Comparison of Mechanical Properties of All SCC Field Mixes

Figure 38 and Figure 40 show a comparison of mixes obtained from the field including the demonstration shaft. It is clear that concrete from drilled shafts 1 and 3, both having lower slump flows, outperformed the concrete from the demonstration shaft.

Cross-Hole Sonic Logging Evaluation of Drilled Shafts

The project Contractor performed Cross-hole sonic logging evaluation on each drilled shaft including the demonstration shaft. The results showed no (major) air pockets or a discontinuity in the integrity of any of the shafts. This means that the SCC mix used was successful in passing through the dense reinforcement layers in the 6 feet diameter shafts. Appendix A shows typical results from the analysis of the CSL of the Drilled Shafts in I-280 Interchange.

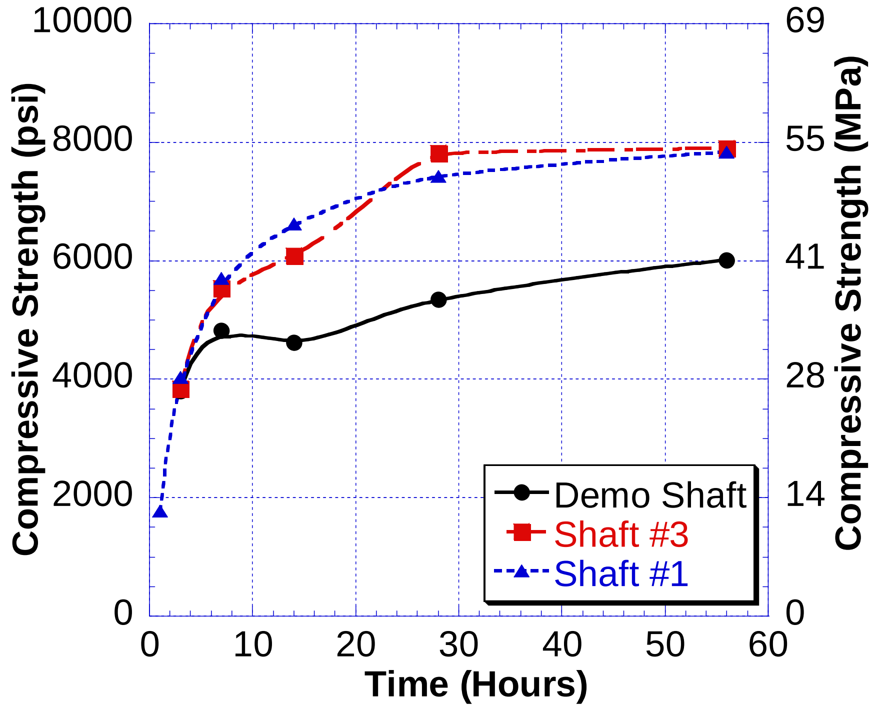


Figure 38. Comparison of Compressive Strength of Field Mixes

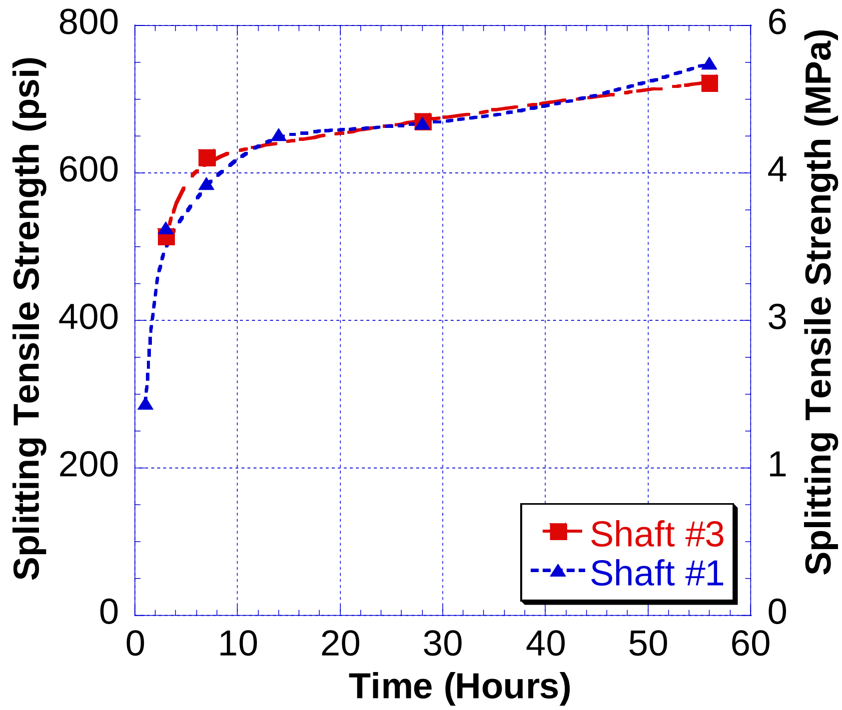


Figure 39. Comparison of Splitting Tensile Strength of Field Mixes

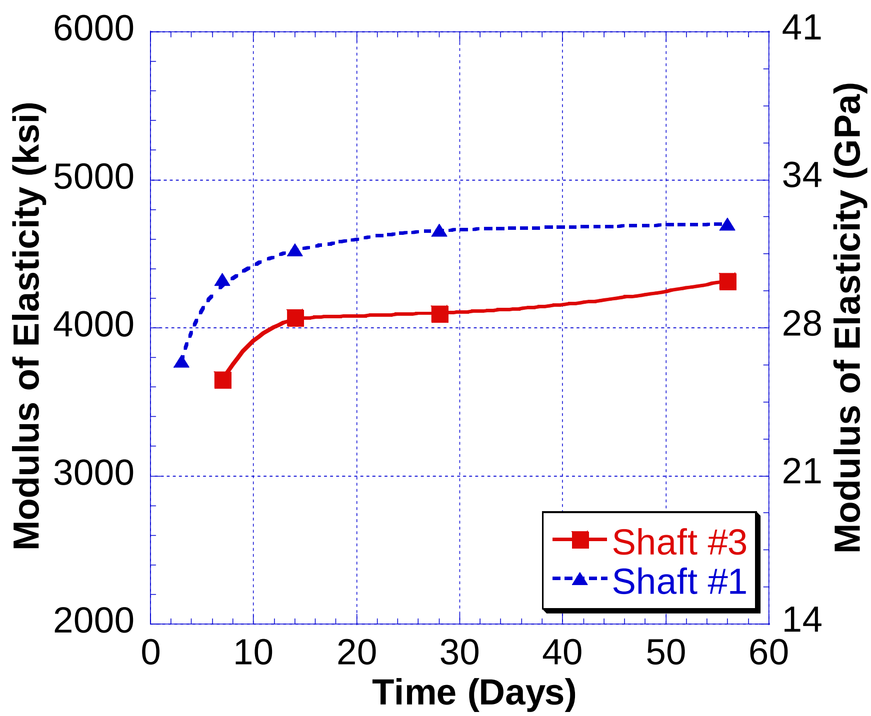


Figure 40. Comparison of Modulus Elasticity of Field Mixes

RECOMMENDATIONS AND CONCLUSIONS

The following conclusions and recommendations could be made from this study

1. There are no significant changes in compressive strength between SCC and normal/conventional concrete.
2. The modulus of elasticity of SCC is slightly lower than that of normal/conventional concrete but its tensile splitting strength was higher. The reduction in the elastic modulus was about 5% and the increase in the tensile splitting strength was about 10%. Nonetheless, the modulus of elasticity of SCC containing supplementary cementitious materials increases at a higher rate with time than regular SCC.
3. SCC has higher drying shrinkage than normal/conventional concrete and HPC. The drying shrinkage of SCC was approximately 30% higher than that of normal/conventional concrete and approximately 40 % higher than that of HPC. In addition, fly ash is the best overall pozzolans for controlling the drying shrinkage of SCC with a 10 % reduction over normal SCC.
4. The performance of SCC under rapid chloride permeability testing (ASTM C1202) is greatly enhanced with the addition of fly ash and silica fume especially at 56 and 90 days. There is a 70% reduction in the amount of charged passed with the addition of silica fume and fly ash.
5. Performance of the SCC obtained from the drilled shafts in Phase II was found satisfactory. However, for the Demo shaft, the slump flow measured was over the upper specified limit of 28 inches. Additionally, it is also observed that there is a need to examine various mixes for segregation by applying the Visual Stability Index (VSI) as a screening tool.
6. ASTM Standard J-Ring Test (C1621/C1621M-06 Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring) was successfully used to test the passing ability of SCC. It is suggested that this test be used as a part of quality control measure (along with the regular slump flow test) when a more quantitative result is needed. This is especially true for mixes with superplasticizer only and high coarse aggregate content where the slump flow maybe within the limits of the slump flow test but may segregate when passing through the J-ring.

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Appendix A – Cross-Hole Logging Tests

Table 22 – Summarized results of CSL Testing for Demo Drilled Shaft #1 on I280 Interchange (CHL tests performed by Olson Instruments)

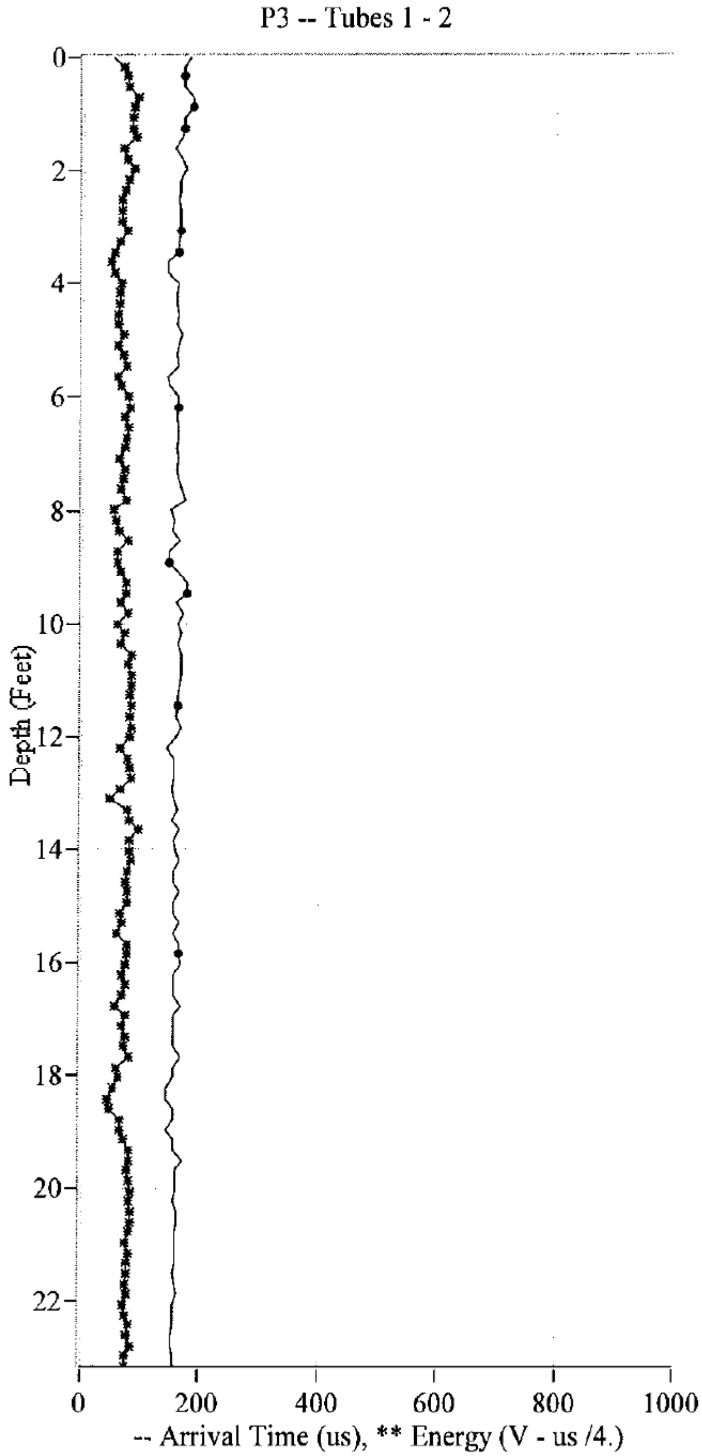
Drilled Shaft No.	Date Tested	Age When Tested	Figure Nos.	Average Compression Wave Velocity, Vc (fps)	Concrete Condition Rating	Anomalous Zones Encountered within the Drilled Shaft (Tube Pair, Depth, PVR)
D1	12/15/06	4 days	1-10	13,000 fps to 14,300 fps	G	

Notes: All depths are measured from the top of concrete.
The percent velocity reduction (PVR) is calculated based upon the measured compression wave velocity in sound concrete measured adjacent to the anomalous zone.

Table 23 – Summarized results of CSL Testing for Demo Drilled Shaft B3 on I280 Interchange (CHL tests performed by Olson Instruments)

Drilled Shaft No.	Date Tested	Age When Tested	Figure Nos.	Average Compression Wave Velocity, Vc (fps)	Concrete Condition Rating	Anomalous Zones Encountered within the Drilled Shaft (Tube Pair, Depth, PVR)
B3	4/20/07	7 days	1-9	12,000 fps to 13,000 fps	G	

Notes: All depths are measured from the top of concrete.
The percent velocity reduction (PVR) is calculated based upon the measured compression wave velocity in sound concrete measured adjacent to the anomalous zone.



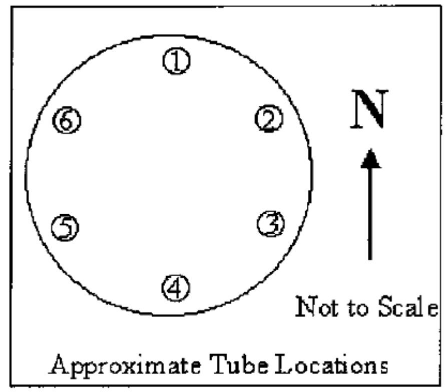


Figure 41 – Typical CSL for Drilled Shaft B3 (CHL tests performed by Olson Instruments)

Table 24 – Summarized results of CSL Testing for Demo Drilled Shaft P1 on I280 Interchange (CSL tests performed by Olson Instruments)

Drilled Shaft No.	Date Tested	Age When Tested	Figure Nos.	Average Compression Wave Velocity, Vc (fps)	Concrete Condition Rating	Anomalous Zones Encountered within the Drilled Shaft (Tube Pair, Depth, PVR)
P1	5/15/07	15 days	1-9	12,000 fps to 13,000 fps	G	After water added to tube
P1	5/15/07	15 days	10-12	12,000 fps to 13,000 fps	Q - debonding	Before water added to tube

Notes: All depths are measured from the top of concrete.
The percent velocity reduction (PVR) is calculated based upon the measured compression wave velocity in sound concrete measured adjacent to the anomalous zone.

Table 25 – Summarized results of CSL Testing for Demo Drilled Shaft P1 and P2 on I280 Interchange (CSL tests performed by Olson Instruments)

Drilled Shaft No.	Date Tested	Age When Tested	Figure Nos.	Average Compression Wave Velocity, Vc (fps)	Concrete Condition Rating	Anomalous Zones Encountered within the Drilled Shaft (Tube Pair, Depth, PVR)
P1	5/8/07	7 days	1-9	12,000 fps to 13,000 fps	G	Debonding in top 10 ft. of tube 2
P1	5/8/07	14 days	10-18	12,000 fps to 13,000 fps	G	

Notes: All depths are measured from the top of concrete.
The percent velocity reduction (PVR) is calculated based upon the measured compression wave velocity in sound concrete measured adjacent to the anomalous zone.

This CSL rating criteria categorizes abrupt increases in the signal arrival times that correspond to decreases in the average signal velocity of the material between the test probes. These abrupt changes are a result of one or more of the following three conditions: (1) increased signal path length as the signal travels around a flaw; (2) a decrease in the signal velocity as it travels through a lower velocity material such as weaker concrete, honeycomb, or contaminated concrete; and (3) deterioration of the bond between the access tube and the concrete. Of the three conditions that cause increased signal arrival times, the deterioration of the tube-concrete bond is the least common and is typically identified only in the upper portions of shafts and in shafts with PVC access tubes.

This CSL rating criteria is based on the percentage reduction of the signal velocity through the flawed area versus the signal velocity through sound material immediately adjacent to the flaw. This insures that the signal arrival times used to calculate the signal velocities are measured through the same amount of material, which is very important if a tube pair is not evenly spaced from shaft top to bottom. This CSL criteria is in large part based on experience with ultrasonic pulse velocity measurements of structural concrete, which uses signal velocities to determine material integrity. However, the calculated signal velocities in the CSL testing are reduced by inherent delays due to the slower water, and PVC tube materials. This signal delay yields artificially lower signal velocities for path lengths of 24 inches or less. In contrast, the percentage change in signal velocity between good and flawed material is unaffected by inherent signal delays. The general rating criteria for CSL results appears below.

Rating	CSL Results Indicative of Drilled Shaft Concrete Condition
Good (G)	No signal distortion and decrease in signal velocity of 10% or less are indicative of good quality concrete.
Questionable (Q)	Minor signal distortion and a lower signal amplitude with a decrease in signal velocity between 10% and 20%. Results indicative of minor contamination or intrusion and/or questionable quality concrete. Investigations of anomalies with 10-15% reductions in velocity have identified sound concrete at some sites and flawed concrete at others.
Poor/Defect (P/D)	Severe signal distortion and much lower signal amplitude with a decrease in signal velocity of 20% or more. Results indicative of water slurry contamination or soil intrusion and/or poor quality concrete.
No Signal (NS)	No signal was received. Highly probably that a soil intrusion or other severe defect has absorbed the signal (assumes good bonding of the tube-concrete interface). If PVC tubes are used or if the measurement is from near the shaft top the tube-concrete bonding is more suspect.
Water (W)	A measured signal velocity of nominally V = 4,800 to 5,000 fps. This is indicative of a water intrusion or of a water-filled gravel intrusion with few or no fines present.

Table 26 – Crosshole Sonic Logging (CSL) Condition Rating Criteria (CHL tests performed by Olson Instruments)